A Comprehensive Review on Internet of Things Applications in Power Systems

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***Abstract*—In the realm of power systems, the Internet of Things (IoT) emerges as a transformative force, steering a shift toward sustainable and distributed energy solutions for global economic growth. This comprehensive investigation navigates through various applications of IoT, unfolding its benefits and multifaceted impacts on society, the environment, and the economy. Real-world applications include the integration of renewable energy, automation of power plants, deployment of smart protection devices, and the establishment of smart homes through occupancy sensing and smart meters. This review concludes by reflecting on the transformative role of IoT in power systems, emphasizing its impact, growth opportunities, and the imperative need to address existing challenges. It also serves as a comprehensive exploration of the intricate dynamics surrounding IoT in the power sector, paving the way for informed decision making and future developments.**

***Index Terms*—Case studies, charging stations (CSs), communication, cyber-attacks, electric vehicles (EVs), energy management, Internet of Things (IoT), IoT in energy consumption, power systems, protection devices, real-time monitoring, renewable energy, smart homes.**

I. Introduction

With the development of numerous technical advancements, the world's energy systems have evolved substantially. Historically, electrical systems have been relatively simple. Their basic functions, i.e., generating electricity and directing homes and businesses, were largely unchanged for decades. The operation was straightforward: central power plants transmitted electricity across an extensive transmission and distribution grid. Most of the implementation was top-down with little feedback from the endpoints, but in an era of rapid technological progress in many industries, this paradigm is undergoing a major shift. The root of this change lies in integrating the Internet of Things (IoT) into the electric grid [1].

The increase in household consumption and plug loads depicted in Fig. 1 highlights a significant global trend, coinciding with the intensifying demand for energy worldwide. As this demand rises and the need for sustainable and robust energy practices grows, conventional energy systems are proving their limitations. Challenges, such as load balancing, demand forecasting, renewable energy integration, and grid security, have become key issues. The decentralized nature of emerging energy systems with distributed energy, such as wind turbines, solar panels, and energy storage, adds complexity to grid management tasks [2], [3], [4]. Herein lie the advantages of IoT, with the ability to deliver real-time information from multiple points in the system, facilitate two-way communication, and enable intelligent decision making through advanced analytics. The IoT, as depicted in Fig. 2, is a growing ecosystem of myriad devices, sensors, and actuators connected by communication networks [6]. Each device in this system is capable of storing, transmitting, and frequently processing data, providing an unprecedented level of visibility and spatial control. From smart refrigerators that optimize cooling systems based on user behavior to industrial devices that anticipate their maintenance needs, the IoT's tentacles are

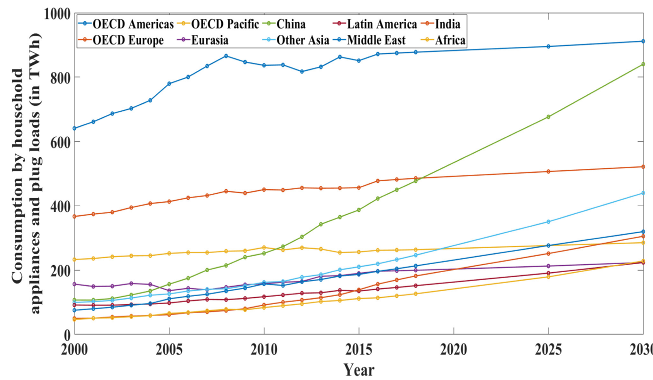

Fig. 1. Increasing household consumption and plug loads across various countries (based on data in [5]).

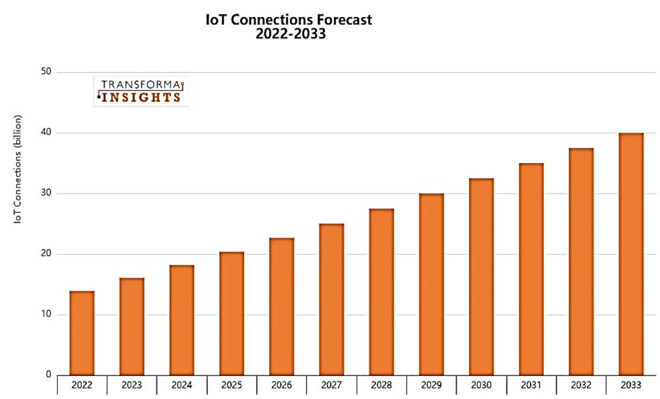

Fig. 2. Increasing number of IoT devices [6].

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spreading across all sectors, and its integration into the power system is not just a logical development but a necessity in the face of ongoing global energy challenges.

However, as with any transformative technology merger, the journey is not without its challenges. Concerns about data security, interoperability of devices from different manufacturers, issues of exclusive growth in the number of devices, and the ever-present challenge of ensuring that the customers get a seamless user experience are some obstacles in the way [7].

The primary objective of this review article is to comprehensively explore the applications of IoT technology within various sectors of the power system. It aims to investigate how IoT can be integrated across different aspects of power generation, transmission, and distribution, with a focus on enhancing efficiency, reliability, and resilience. Additionally, this article includes figures depicting key architectures corresponding to specific applications of IoT across various areas, enhancing the understanding of IoT integration in the power system.

The main contributions of this review article can be summarized as follows.

1) *Exploration of IoT Applications:* This article conducts a comprehensive exploration of works spanning the past decade, with a specific focus on articles published within the last five years. It delves into how IoT technology can be applied in different areas of the power system, including smart grid infrastructure, condition monitoring, protection, cybersecurity, energy management, data privacy, and distributed energy resources (DERs).
2) *Identification of Key Areas:* By delving into these various sectors, the review identifies key areas where IoT has the potential to make significant advancements and improvements in power system operations.
3) *Real-World Case Studies:* This article includes real-world case studies of various companies, demonstrating the practical applications and benefits of IoT in power systems.
4) *Contribution to Knowledge:* Ultimately, this article aims to serve as a valuable resource for researchers interested in understanding the potential of IoT in transforming the power sector.

The subsequent sections are organized as follows: 1) Section II provides foundational knowledge on IoT; 2) Section III delivers a comprehensive analysis in various domains, encompassing generation, transmission, distribution, and consumption of power; 3) Section IV explores real-world case studies of IoT applications in the power sector, assessing their impact on the environment, economy, and society; and 4) Section V delves into the obstacles hindering the integration of IoT in power systems, offering insights into potential solutions.

This article concludes by summarizing key insights in its final section.

II. Foundations of IoT in Power Systems

The IoT is a term that frequently resounds with promise and potential in today's interconnected world. IoT is fundamentally about establishing a connection between physical and digital objects to facilitate an easy interchange of data. Combining this potential with our power systems will serve as a robust framework for our contemporary society. The implications are significant, and to fully grasp this synergy, we must first understand the fundamental concepts of IoT and how they relate to power systems.

A. Concept of IoT

Various definitions highlight the essence of IoT. The European Union (EU) defines it as the interconnection of computers forming a network of items, while the International Telecommunication Union (ITU) describes IoT as universal connectivity for anything, anytime, anywhere [8]. The Internet Architecture Board (IAB) characterizes IoT as the interconnection of smart devices [9]. Essentially, IoT refers to a network of connected devices that can communicate with one another through the Internet, ranging from basic sensors to complex pieces of equipment. These IoT-enabled entities, as opposed to conventional devices, have the capacity to gather, send, and occasionally process data, enabling smarter operations and better informed decision making. It is predicted that there will be more than 43 billion devices connected to the Internet by the end of 2023 [10]. They will produce, exchange, gather, and assist operators in using data in a variety of ways.

B. Historical Evolution of IoT

Since the birth of the World Wide Web in 1989, there has been a growing trend of linking objects to the Web. The Trojan Room coffee pot can be considered as one of the earliest examples of such a combination [12]. In 1990, John Romkey introduced an Internet-connected appliance, a toaster that could be operated remotely through the Internet. In 1994, Steve Mann developed the WearCam, a device for near real-time automation. Later, in 1997, Paul Saffo presented the first description of the sensors and suggested possible mechanisms. In 1999, Kevin Ashton, who was the executive director of the MIT AutoID Center, coined the term "IoT." In the same year, they developed a global identification system based on radio frequency identification (RFID) technology. In a major step toward commercializing the IoT, electronics giant LG revealed plans in 2000 to introduce smart refrigerators. This advanced refrigerator was designed to independently test and monitor the replenishment of its food inventory [13]. LG's initiative marked a pivotal moment in the commercialization of the IoT, laying the foundation for subsequent advancements in smart home technology and the seamless integration of IoT capabilities into consumer products. In 2003, Savi Technologies secured a $90 million contract from the Department of Defense. Under this agreement, Savi was tasked with delivering RFID equipment and related software solutions to the U.S. military [14]. In 2005, Wal-Mart initiated its RFID technology after conducting trial runs at its distribution centers [15]. In 2008, several corporations established the Internet protocol (IP) for smart objects (IPSOs) Alliance with the aim of endorsing the application of IP within "smart objects," thus expanding the reach of IoT. Many industry giants like Bosch, Cisco, SAP, Google, Intel, etc. became its members [16]. In December 2017, the IPSO Alliance and the

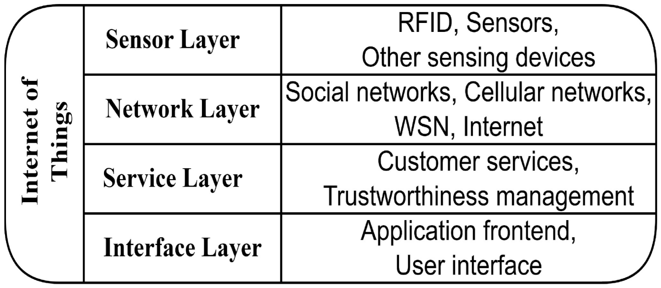

Fig. 3. Basic architecture of IoT (modified version of Fig. 1 in [11]).

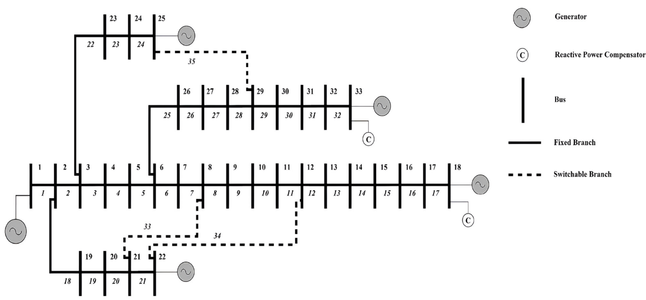

Fig. 4. IEEE 33 bus distribution system [21].

Open Mobile Alliance collaborated to establish the IPSO smart objects working group (IPSO WG), with a focus on facilitating communication among IoT devices and establishing worldwide interoperability based on open standards [17]. In 2015, the U.K. government allocated a substantial £ 40 million in its budget to support the advancement of scientific and technical research, specifically focusing on the IoT [18]. This financial commitment aimed to foster innovation and progress in the field of IoT, reflecting the government's recognition of the importance of emerging technologies in shaping the future landscape of science and technology.

The IoT architecture comprises a collection of elements working together to enable seamless communication and interaction [19]. Essential technologies under IoT include RFID devices, wireless sensor networks (WSNs), sensors, global positioning systems, cellular networks, and services [20]. A basic architecture of IoT is structured into layers, which include the sensing layers, network layer, service layer, and interface layer as shown in Fig. 3 [11].

C. Intersection of IoT With Traditional Power System

A traditional power system, similar to the configuration depicted in Fig. 4 illustrating the IEEE 33 bus distribution system, comprises a complex interplay of components, including generators, transmission lines, loads, and reactive compensation devices [21]. The effectiveness of such systems critically depends on robust monitoring and seamless communication among their components for several reasons. First, within a power system, the coordinated operation of diverse components is paramount to ensure uninterrupted electricity supply. Effective monitoring enables operators to swiftly identify deviations or abnormalities in component performance, such as voltage fluctuations or instabilities, which could potentially lead to equipment failure or service interruptions. Second, seamless communication between components is essential for real-time coordination of their actions and responses. For instance, in response to sudden surges in electricity demand, generators must promptly adjust their output to maintain system stability. Without efficient communication, such adjustments may be delayed or inefficient, leading to voltage drops, frequency fluctuations, or even blackouts.

Moreover, rapid communication is essential in the event of faults or outages, facilitating the swift isolation of affected areas and the restoration of service to customers. Effective monitoring and communication also empower utilities to implement proactive maintenance strategies, mitigating the risk of equipment failures and prolonging asset lifespan. By continuously monitoring critical components, such as transformers or circuit breakers, utilities can detect signs of wear or impending failure early on and take preventive action before breakdowns occur. The integration of renewable energy resources further underscores the importance of effective monitoring and communication. Renewable energy sources, such as solar and wind power, exhibit inherent variability, necessitating real-time monitoring to accurately forecast and manage their contributions to the overall power system. Seamless communication between renewable energy generators and grid operators facilitates their integration into the grid, ensuring stability and efficiency. In addition to these challenges, energy theft poses a significant problem in traditional power systems. Unauthorized access to electricity distribution networks for personal use or resale can result in revenue loss for utility companies and higher costs for consumers. The application of IoT presents promising solutions to these challenges, as detailed in Section III.

In summary, some of the most essential challenges in traditional power systems are fault detection, blackouts, load forecasting, energy theft, and transmission losses. In India, around 30% of electrical energy is lost in the transmission [22]. IoT has the potential to seamlessly merge the resources of communication and electric power systems, enhancing the overall efficiency of the power system and paving the way for the establishment of smart grids. Smart grids are advanced version of the traditional electrical grid that integrates information, control, and communication technologies to improve security, efficiency, reliability, and economic performance across electricity generation, transmission, distribution, and consumption [23]. Since 2007, the U.S. commenced its shift toward incorporating IoT technology into its grid system [24]. For IoT to be effectively integrated into power systems, it is essential to focus on consistent line monitoring and real-time control across all grid operating parameters. To assess the tangible advantages and identify appropriate technologies for the smart grid, the Ministry of Power under the Indian Government initiated 14 pilot projects across the country, each showcasing different smart grid features. The Puducherry Smart Grid initiative is one of the pilot projects which is being developed jointly by Power Grid Corporation of India Ltd. (POWERGRID) and Puducherry Electricity Department (PED) [25]. As per recent

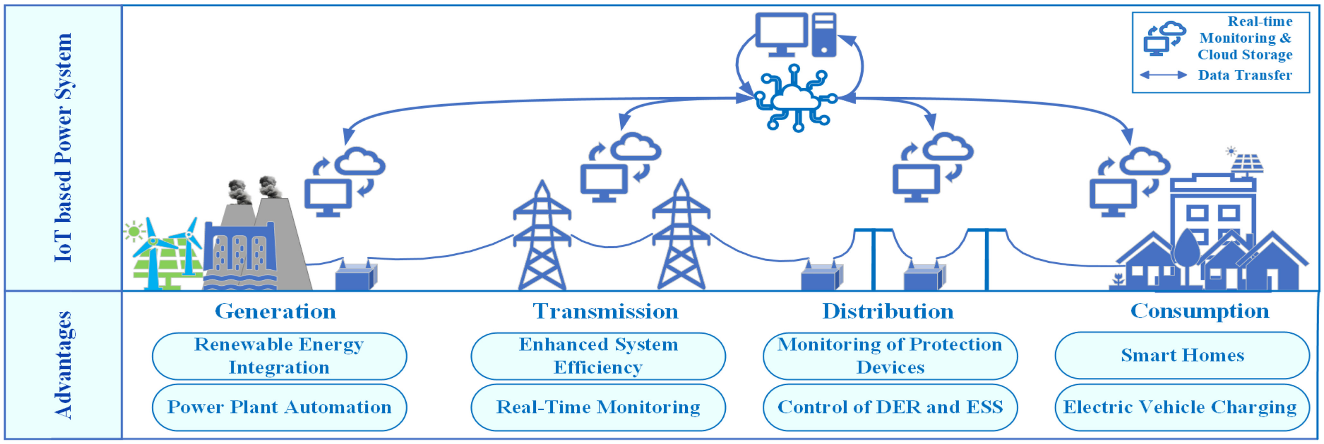

Fig. 5. Visualization and advantages of IoT-based power system.

updates, the Puducherry Smart Grid project, which deployed around 28 910 smart meters, has been completed, resulting in a 6.6% reduction in aggregate technical and commercial losses and a 7% improvement in billing efficiency [26], [27]. This underscores the transformative impact of integrating IoT technologies into power systems, enabling the creation of a more efficient, resilient, and sustainable energy infrastructure capable of meeting the evolving challenges of modern society. Various other real-word applications of IoT in power systems are discussed in Section IV.

III. Applications and Benefits of IoT Integrated Power System

Integrating the IoT into the electricity grid has not only modernized our energy system but also delivered a myriad of benefits that impact the field of electricity generation, distribution, and consumption [28]. These benefits range from improved efficiency and reduced operating costs to the use of innovative applications that optimize energy utilization. The advantages of integrating digital technologies into smart power grids, shown in Fig. 5, and IoT-enabled applications are discussed in detail in the following sections.

A. Integration of Renewable Energy Resources

The world is currently at a critical stage in the battle against climate change. The Intergovernmental Panel on Climate Change, operating under the United Nations, has issued a clear warning that in order to keep global temperatures below 1.5°C, greenhouse gas emissions must be reduced by 43% by 2030 [29]. Since 2010, advancements in renewable energy technologies have drastically lowered the cost of solar, wind, and battery storage systems by 85%. A wider range of policies and regulations for energy consumption have stimulated improvements in energy efficiency and accelerated the adoption of renewable energy [30]. Current studies indicate that approximately one-third of the world's electricity is derived from renewable sources [31]. In 2023, the capacity additions in renewable energy surged to an estimated 507 GW, with solar and wind energy jointly contributing to 96% of the total capacity additions [32]. By harnessing the transformative capabilities of IoT, the generation sector will be able to anticipate and manage energy demand more dynamically, marking a significant step forward in our global efforts to promote sustainability. Additionally, considering the varying nature of wind and solar energy output, forecasting errors tend to grow, complicating transmission network management [28]. However, digital advancements and analytics can increase forecasting accuracy, with companies like general electric (GE) suggesting a potential rise to 94% from 88% [33].

Building on the recent advancements in forecasting accuracy combined with the vast potential of IoT in the renewable energy domain, we observe the key role of digital technologies in addressing the challenges associated with renewable energy. In [34], the important role of solar energy as a sustainable energy solution in today's environmental context is emphasized. The research analyzes the unpredictability of solar radiation, which poses a significant risk to investing in solar projects. To mitigate these uncertainties, the study presents a hedging system that seamlessly integrates IoT capabilities. Edge-based models are developed by extracting data from solar panels and weather sensors via IoT, providing highly accurate solar radiation forecasts. The system establishes two prediction models: 1) the precision predictive model (PPM) and 2) the light predictive model (LPM), designed using machine learning (ML) algorithms. Notably, with the help of random forest regression (RFR) [35], this model obtained R-squared values of 0.841 and 0.828 and correlation coefficients of 0.917 and 0.910 for PPM and LPM, respectively. This hedging strategy not only guarantees brokers (seller side) a steady revenue stream, evidenced by a Sharpe ratio [36] of 3.354, but also promises investors (buyer side) sizable payoffs during times of diminished solar radiation. A detailed flowchart that provides insights into the operations of the hedging system is illustrated in Fig. 6. Pawar and TarunKumar [37] addressed the challenges of efficient energy utilization from renewable sources in the context of ever-increasing power consumption. An energy management system is presented as a solution that monitors and optimizes energy usage and costs, efficiently allocates energy sources, integrates sustainable power, and ensures reliability and safety while balancing supply and demand within operational constraints

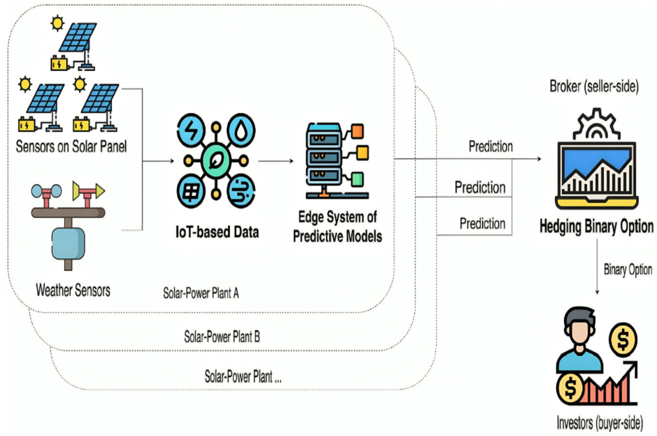

Fig. 6. Hedging system for solar power generation [34].

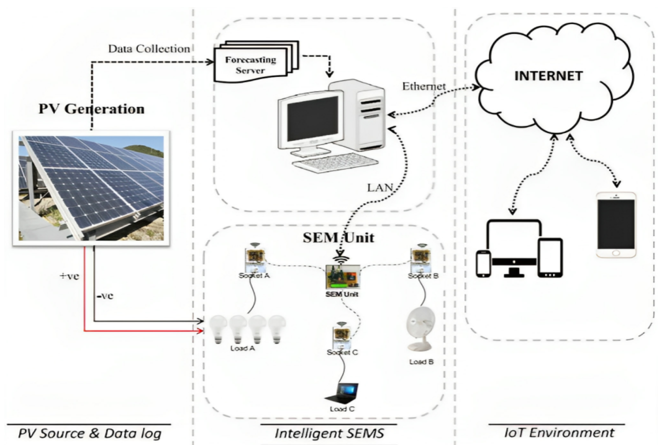

Fig. 7. Depiction of ISEMS [37].

and uncertainties. The authors introduce the intelligent smart energy management systems (ISEMSs), depicted in Fig. 7, aimed at enhancing energy demand management within a smart grid that heavily incorporates renewable sources. The primary objective is to ensure day-ahead planning coupled with precise energy forecasting. A comparative study of various prediction models like artificial neural network (ANN), particle swarm optimization (PSO)-based ANN, support vector machine (SVM), and PSO-based SVM was undertaken, with the PSO-based SVM regression model emerging as the most accurate. The architecture of ISEMS is divided into three crucial stages. First, a photovoltaic (PV) generation and data collection module is responsible for harvesting and recording energy data. Next, an intelligent energy management system harnesses this data, utilizing the prediction model (PSO-based SVM) for optimal energy distribution and planning. Lastly, an IoT platform provides users with real-time access to energy details and facilitates appliance management. Accurate solar energy forecasting is also important for IoT systems to operate seamlessly and sustainably, as highlighted in [38]. The study integrates diverse ML techniques with accessible public weather forecasts to predict solar energy for a vast number of IoT devices over a medium time frame. The system developed can continuously learn and adapt to the addition of new devices and adjust its predictions without manual oversight. After testing a variety of ML techniques, the combination of RFR with specific weather data proved to be the most effective, reducing errors in prediction by 20% compared to other techniques. An important feature of this system is its ability to recognize differences, like the size of solar panels, and adjust its learning. This means IoT devices can operate more efficiently, using energy when it is best available. This research could also lead to smaller and more efficient setups for capturing and storing solar energy, making the whole system more sustainable and cost-effective.

Advancements in wind power generation have made similar breakthroughs to solar energy by integrating IoT and ML. The growing implementation of wind energy across the globe, though promising, has confronted challenges arising from turbines' remote locations and increased susceptibility to failures. To mitigate the associated maintenance concerns and enhance grid stability, an IoT monitoring system has been devised in [39]. This system integrates a robust FPGA-CPU hybrid controller, facilitating real-time processing and efficient multitasking. Specifically, the field-programming gate array (FPGA), with its reliable parallel processing capabilities, ensures that various tasks are handled without resource conflicts, while the CPU oversees crucial data logging and network-related activities. Essential components supporting this structure include an uninterruptable power supply, high-capacity network-attached storage (NAS), and a hardware firewall, ensuring data integrity, security, and real-time accessibility. Operationally, the system functions in a structured manner, from data acquisition to processing and then organized logging. A distinct advantage of this integrated system lies in its dual-monitoring capability; it can concurrently track both the wind turbines' operational condition and potential subsynchronous control interactions, offering operational efficiency. This system not only promotes real-time monitoring but also paves the way for comprehensive post-event analysis and wind energy management. In another study [40], researchers delve into the economic benefits and opportunities of wind power generation with its inherent challenges, such as its unpredictable nature, which complicates its integration into the grid. To better predict wind power, an enhanced predictive model using SVM optimized with genetic algorithm (GA) is introduced. The model's efficacy was tested on a 10-day data set from a wind farm, sampled every 5 min. It was noted that while improper parameter setting in traditional SVM models can hinder prediction accuracy, the GA-SVM displayed enhanced predictive capabilities. Furthermore, the robustness of this method was confirmed even when faced with flawed data, showcasing its resilience against inaccuracies. The study demonstrates that by optimizing certain parameters in prediction models using optimization techniques, the forecasting of wind power can be significantly improved, potentially leading to more efficient and reliable use of wind energy in the future. In another endeavor to integrate wind energy into the Brazilian power grid, the challenge of efficiently managing this unpredictable energy source has been taken up, as elaborated in [41]. Utilizing real data from wind turbines situated in Ceara State, Brazil, the study employed a

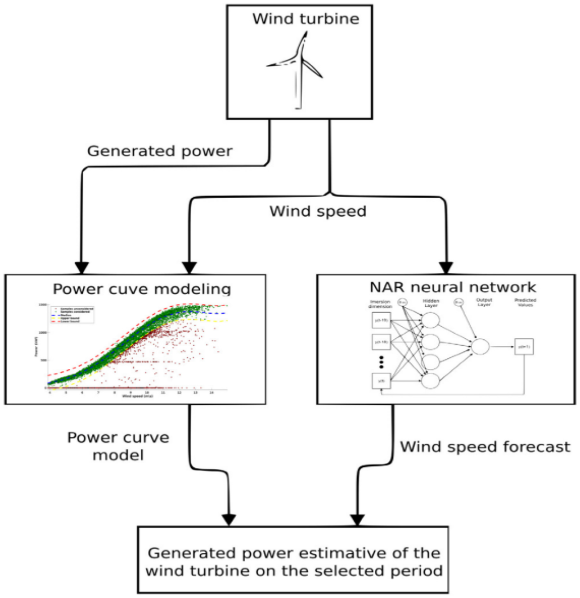

Fig. 8. Wind estimation process [41].

combination of logistic regression and nonlinear autoregressive (NAR) neural networks to forecast wind speeds. Through this method, the study witnessed a decrease in power generation estimate errors to just 29W over a five-day span, outpacing the manufacturer's estimates by 63%. Their methodology, depicted in Fig. 8, prioritizes a sequential approach comprising wind speed estimation, wind turbine power curve modeling, and energy production forecasting. Furthermore, comparing the study with related research, one work [42] managed to reduce energy production estimate errors significantly, but their predictions were confined to just an hour. On the other hand, Rebouças Filho et al. [41] extended its forecasting to a week, achieving results that are over five times more accurate. Another study [43] showed encouraging results in wind speed predictions, yet was not explicit about the forecasting timeframe. Research findings from [44], derived mainly from data in Taiwan, indicated different wind speed patterns than those observed in Ceara. Moreover, the data from [45], also based on Taiwan, seemed to be constrained by the region's more consistent wind speeds. One distinct feature of [41] was the introduction of a specialized power curve tailored for Ceara's diverse wind patterns across a 4-month period. This approach, with an IoT framework, can process vast data from wind turbines and sensors and offer wind farm managers vital insights, helping them plan more effective and sustainable energy systems.

B. Power Plant Automation

The introduction of the IoT has indicated a transformative period in industrial automation, pushing the boundaries of efficient production while ensuring cost optimization and judicious utilization of manpower [46]. Within this vast realm, Thermal Power Plants, which have historically relied on programmable logic controllers (PLCs) and distributed control systems (DCSs) to maintain and regulate critical parameters, such as humidity, temperature, and pressure, are undergoing profound technological shifts. The research carried out in [46], delves deep into the development of a smart simulation system, employing an intricate interplay of sensors, data mining techniques, and complex modeling. By leveraging IoT, the system ensures that each boiler in the plant is interconnected through sensors, allowing for real-time data transfer to a centralized IoT application. This ensures rapid remote monitoring and precision adjustments to dynamic parameters, exponentially reducing the risk of mishaps. Additionally, a unique innovation proposed is a virtual knob mechanism facilitated by an IoT device, granting technicians the ability to tweak furnace parameters from distant locations. The overarching objective is to transition from labor-intensive, manual oversight to a sophisticated, automated paradigm that amplifies operational efficiency and safety. This article offers not just a framework for automating power plant operations using IoT but also presents a holistic analysis of data flow mechanisms, the importance of recognizing simulated patterns, and the proper synchronization of the entire system. In another study [47], the emphasis on the integration of IoT into industrial sectors has been further explored, with a specific focus on high-tension (HT) motors in thermal power plants. These HT motors, pivotal components in the power generation process, operate at high voltages, such as 3.3, 6.6, and 11 kV. A breakdown or malfunction in these motors can lead to substantial operational disruptions, translating to significant economic implications for the entire facility. The research sheds light on an IoT-based remote monitoring system tailored explicitly for these HT motors. Through a synergy of current, vibration, speed, and voltage sensors, the system can meticulously gauge and relay real-time operational data to an Arduino controller. With the assistance of a Wi-Fi module, module 8266, this data is then transferred to a cloud storage solution, ensuring timely access and analysis. The BLYNK IoT platform provides a user-friendly interface through its mobile application. This app becomes a conduit for real-time monitoring, alerts, and even control mechanisms. The proactive nature of the system ensures that any deviation in the motor's operational parameters triggers immediate notifications, alongside an automatic shut-down feature powered by an integrated relay system. The research carried out in [47] underscores the paramount importance of leveraging IoT in thermal power plants, paving the way for enhanced operational efficiencies, mitigated risks, and reduced downtimes. These findings underscore the unparalleled potential of IoT in revolutionizing thermal power plant functionalities while also providing areas for future explorations in the domain.

The integration of the IoT in thermal power plants has marked a significant stride in advancing industrial automation; similarly, its adaption in hydroelectric power systems presents a promising frontier in optimizing water-based energy generation and management. Hydropower holds great promise in addressing the global energy demand. Nevertheless, challenges, such as silt erosion and cavitation, can significantly diminish the efficiency of hydro turbines [48]. The architecture, depicted in Fig. 9, equipped turbines with an array of specialized sensors to capture parameters like voltage, current,

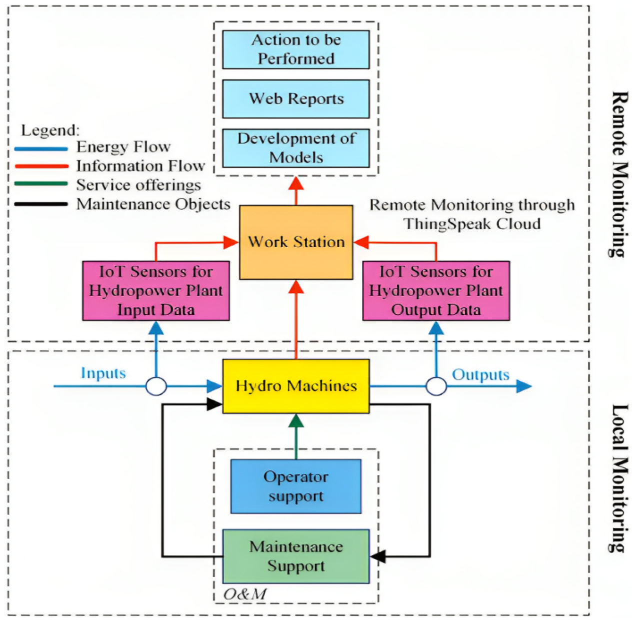

Fig. 9. Monitoring of hydro machines [48].

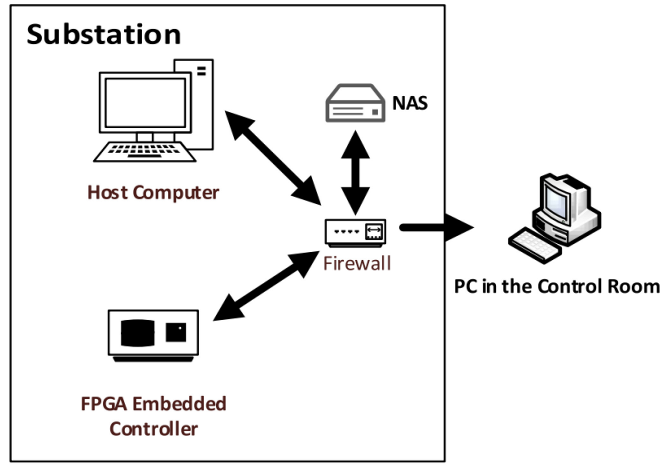

Fig. 10. Real-time monitoring system framework based on IoT [61].

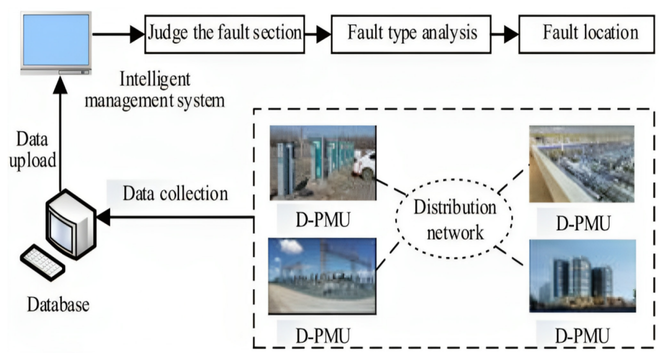

Fig. 11. D-PMU data transfer and fault location [62].

and vibration. The ESP8266 Wi-Fi module played a pivotal role in transmitting this data seamlessly to the ThingSpeak cloud platform. Numerous studies have shown the advantages of IoT and similar digital technologies in enhancing power monitoring [49], [50], [51], [52]. For instance, Saleem et al. [53] identified IoT-enhanced smart grid systems as the forefront of future grids, addressing the existing constraints of unidirectional information flow, escalating energy demand, and security issues. Similarly, Myint et al. [54] showcased how IoT combined with SCADA can offer holistic insights into power, current, and other key parameters. The developed model in [48] exhibited an R-squared value of 0.9693 in predicting hydro turbine conditions, with a minimal MAPE of 0.67% and an RMSPE of 0.89%. Additionally, for the power factor predictions, the system achieved an R-squared value of 0.9503, coupled with a MAPE of 0.798% and RMSPE of 0.91%. These findings align with the pivotal role of IoT, AI, and cloud computing in energy sectors [50], [52], [55], [56], [57], [58], [59], [60]. While the study's primary focus remained on Francis turbine-based hydropower plants, it explains the system's broader applicability to other hydro turbines. This adaptability, combined with the potential integration of advanced ML, could steer the industry toward more precise forecasting, ensuring optimal operation and energy generation in the future. Additionally, researchers in [49], illustrated how the confluence of IoT and WSNs amplified dam safety monitoring, underscoring the unprecedented enhancements these technologies bring to energy monitoring.

C. Enhanced System Efficiency and Real-Time Monitoring

In the present scenario, ensuring grid resilience and a stable electricity supply has become more challenging due to the rise of DERs and the aging infrastructure of transmission and distribution networks. Traditional grids, which were once large and centralized, are now witnessing the emergence of new configurations where the stakeholders are more distributed, and maintaining real-time monitoring and regular communication with one another is essential.

In [61], the role of IoT in enabling data sharing among objects through diverse communication channels is explored. An advancement, the Industrial IoT (IIoT), combines data acquisition, communication, and real-time network processing. The study introduces the development and implementation of IIoT-centric monitoring systems for power substations, by taking advantage of the speed and reliability of FPGAs. By utilizing an FPGA-embedded controller, the system ensures real-time tracking of essential substation metrics, ranging from voltage fluctuations and breaker statuses and transformer temperature readings. A significant feature is the integration of high-resolution timestamps using industrial-standard GPS for synchronizing. In this IIoT-centric monitoring system, NAS serves as the primary data storage solution. In static and transient environments, data is transmitted over a local area network (LAN), providing system operators with remote access and real-time insight, as shown in Fig. 10. Additionally, the system successfully recorded and analyzed fault events after the installation of the substation at the Texas Petrochemical facility, providing valuable insights for future prevention strategies. Kong et al. [62] developed a power IoT-based monitoring and evaluation framework aimed at enhancing the reliability and scalability of power distribution systems. This framework supports various applications, such as fault analysis and data gathering. A notable method introduced is the fault location method, which factors in distribution phasor measurement unit (D-PMU) information and network symmetry features. Using the D-PMU measurement, the experiment identifies fault sections and types through the phase difference of negative and positive sequence currents. Unique location algorithms were presented based on the distribution network's load symmetry. The study highlights the importance of real-time and accurate D-PMU measurements, suggesting that they are critical to accurately obtaining the fault location. Fig. 11 depicts the D-PMU information communication and fault location function module. In [63], the integration of distribution static compensator (DSTATCOM) with IoT technology is explored to address the issue of low-power factor in distribution lines. This article commences by highlighting the significance of power factor improvement in distribution lines and the role of DSTATCOM as a vital device for mitigating power quality problems. The control algorithm for DSTATCOM, using the Instantaneous p-q theory and hysteresis current controller, is presented. This article then delves into the application of IoT technology for control of the distribution line and real-time monitoring. It details the software design for low-power factor discrimination using Java programming integrated into MATLAB. The communication module is described, emphasizing its role in timely notification through Gmail when low-power factor conditions are detected. Simulation results in MATLAB/Simulink demonstrate the effectiveness of the proposed system, showcasing how DSTATCOM, when triggered, rectifies power factor fluctuations. IoT is also integrated into the grid to reduce transmission losses. In [64], a methodology for reducing line losses in Pakistan's electricity transmission and distribution system is proposed. The methodology proposed in the system involves two-way communication between electrical utilities and consumers to inform which electrical devices need electricity and, according to the demand, power will be supplied; otherwise, the electrical path will remain unsupplied. Similarly, in [65], IoT is used to monitor the type of power loss that occurred, and the precise location of the power loss area is determined using Google Maps, and then the information is sent to the electricity board via SMS automatically. In [66], a cutting-edge IoT infrastructure emerges as a transformative solution for addressing the intricate challenges of powering and monitoring remote and isolated areas. At the heart of this framework is the IoT remote terminal unit (RTU) incorporating digital and analog inputs and outputs. Operating as the central hub of connectivity, the IoT RTU engages with field devices through the robust Modbus communication protocol. The researchers harness the capabilities of AVEVA Edge 2020 as the designated IoT SCADA system, offering an advanced suite for real-time data control and monitoring [67]. Notably, the integration with the ThingSpeak cloud adds a layer of flexibility, serving as an intermediary IoT server that facilitates communication between the IoT RTU and the SCADA system. The digital and analog I/Os of the IoT RTU are utilized to minimize data transfer to

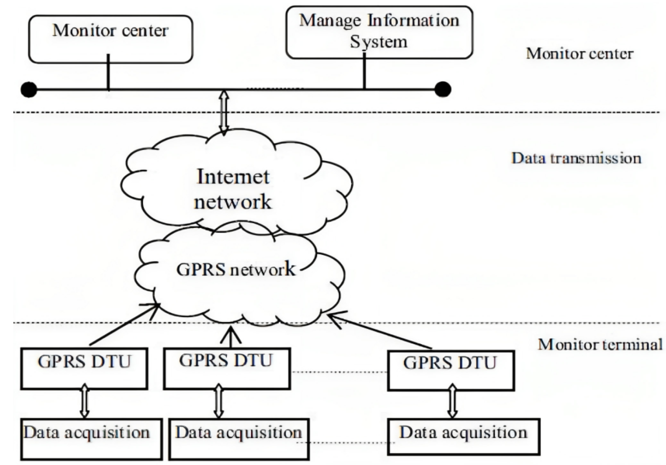

Fig. 12. Monitoring system architecture of distribution transformer [68].

the cloud, ensuring efficiency and optimizing local control in scenarios of communication loss. The adoption of the secure MQTT protocol underscores the importance of system security, addressing potential challenges related to privacy and data protection in the IoT realm. The study's focus on remote water wells and cellular communication towers showcases the practical application of this IoT infrastructure, emphasizing its versatility across different contexts. One major contribution of this IoT infrastructure becomes particularly evident in its role as a power management tool. By continuously monitoring and adjusting power flow, the system ensures optimal energy utilization, minimizing waste and maximizing the efficiency of different power sources.

Another common use of IoT in the power sector is condition monitoring and predictive maintenance of assets [69]. Condition monitoring is a process that involves tracking the operating characteristics of a machine to identify changes and trends that can indicate the need for maintenance before significant deterioration or failure occurs [70]. In [68], the crucial role of electrical transformers in the electricity transmission and distribution process is emphasized. Highlighting the transformer's significance and cost implications in the electrical sector, this article presents a mobile embedded system designed for real-time monitoring of distribution transformer parameters like current, temperature, oil level fluctuations, humidity, and vibration. A dedicated remote terminal, equipped with an 8-channel analog-to-digital converter (ADC), is installed at the transformer's location to capture and record the mentioned parameters. The system is programmed to issue immediate alerts via mobile notifications and to monitor units whenever any parameter deviates from predefined limits. The core components of this monitoring system include the RTU, a transmission network integrating GPRS and public networks, and monitoring node stations, all interconnected using the GSM-GPRS wireless telecommunication network as shown in Fig. 12. Recognizing the challenges posed by unmanned transformer sites, the authors introduce a two-way communication system ensuring uninterrupted monitoring. With its emphasis on early detection, the system's design prioritizes preventing major breakdowns,

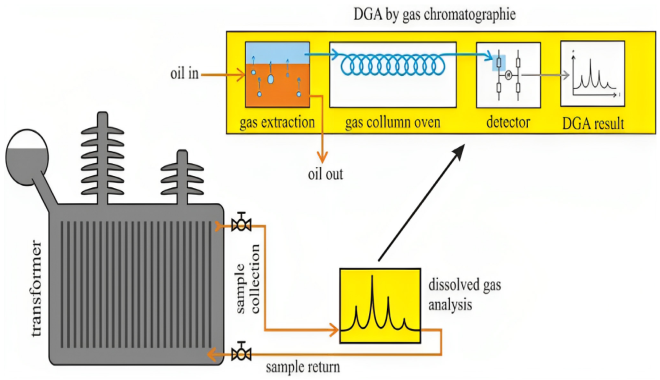

Fig. 13. Transformer equipped with an online DGA system [72].

aiding utilities in enhancing transformer power line protection, and ensuring timely interventions. Hashemi and Dikmen [71] emphasized the imperative nature of not only optimizing transformer design for increased efficiency and lifespan but also implementing continuous monitoring to avert potential failures. The proposed solution revolves around the evaluation of the health index (HI) for oil-immersed transformers through an innovative IoT-based monitoring system. Various methods for assessing transformer health are discussed, encompassing visual inspection, electrical and mechanical testing, oil testing, and utility data analysis. Of particular significance is the dissolved gas analysis (DGA), which emerges as a crucial tool for fault diagnosis. This article meticulously outlines the application of DGA, the gases analyzed, and the diverse fault types it can identify. The Duval Triangle and Rogers Ratio methods are introduced as effective means for calculating a DGA-based HI. The authors further propose a real-time monitoring system employing online DGA integrated within an IoT platform, illustrated by a transformer equipped for continuous gas level monitoring. Fig. 13 illustrates a transformer equipped with an online DGA system. Notably, this article underscores the importance of combining DGA with other data sources for a holistic assessment, incorporating ML algorithms for thorough analysis. This approach not only enhances reliability but also optimizes the overall efficiency of power grids. As industries increasingly adopt IoT solutions, the findings from these research are set to make a significant contribution to the ongoing discourse and implementation of connected systems for sustainable and efficient energy management.

D. IoT in Power System Protection

The application of IoT technology in power system protection has become a critical component of ensuring the stability and reliability of electrical grids. This section delves into the integration of IoT in safeguarding power systems through various protective devices. By providing real-time data and remote control capabilities, IoT empowers protective devices to proactively detect faults, mitigate electrical disturbances, and facilitate swift and efficient fault management. This advanced approach not only enhances grid resilience but also paves the way for predictive maintenance, reducing downtime and minimizing disruption to power supply.

Now, showcasing the potential usage of IoT, Machidon et al. [73] introduced the electrical safety (ELSA) power system protection device. ELSA is designed to seamlessly integrate into smart environments driven by IoT technologies. The main objective of this device is to bolster electrical safety by providing rapid disconnection of power in the event of fault occurrences, such as overcurrent, overvoltage, leakage current, and electrical arcs. An advanced communication interface utilizing a data concentrator architecture enables ELSA's real-time monitoring capabilities. This architecture ensures that recorded events can be efficiently accessed via a Web-based interface. Furthermore, the ELSA device offers real-time notifications through email and text messages, thereby enabling timely responses to potential issues. The materials used in constructing the ELSA power system protective device are carefully selected to ensure its reliability and effectiveness. The device is built around a Microchip PIC 16F1829 microcontroller, which possesses the necessary resources, including 1 kB of RAM, an internal 32 MHz, and 14 kB of Flash oscillator, to support its operation. In addition, voltage and current sensors are incorporated into the design to enable accurate monitoring and fault detection. The ELSA device also features a selection of communication modules tailored to different deployment scenarios. These include a 3G module for household use, a LoRa module with a 10 km transmission range for integration into smart city networks, and an RF module for apartment buildings. These modules enhance the ELSA's adaptability to a wide range of applications.

Another study [74], places a significant focus on the development of smart circuit breakers (SCBs), a component within modern power supply systems, and their integration with IoT. These SCBs are meticulously designed to provide varied functionalities. They not only serve as protective devices for power appliances but also continuously monitor grid quality, encompassing parameters, such as excess current, excess voltage, sparking, leakage, and circuit overheating. Another aspect of these SCBs lies in their capability to transmit real-time data to IoT controllers via an open-wired interface, enabling seamless integration into the broader IoT ecosystem. This integration is instrumental in improving power distribution and quality monitoring. Through the IoT framework, these devices collect comprehensive data, facilitating the detection of anomalies and enabling causation analysis. Additionally, the SCBs are engineered to offer manual controls and a display of circuit breaker status. The SCBs also incorporate a feature for arc detection by analyzing the grid spectrum and AC sine-wave form. This approach allows the identification of the source of higher harmonics in the circuit, improving the safety and efficiency of power distribution systems. Similarly, Jose et al. [75] presented an approach to address the need for enhanced reliability and efficiency in low-voltage distribution boards. At the center of their solution is the development of a Smart Distribution Board, which incorporates a solid-state circuit breaker (SSCB). This SSCB is designed with advanced features, including a resistance-based fault current limiter, an anti-parallel thyristor switch, and a snubber circuit, enabling

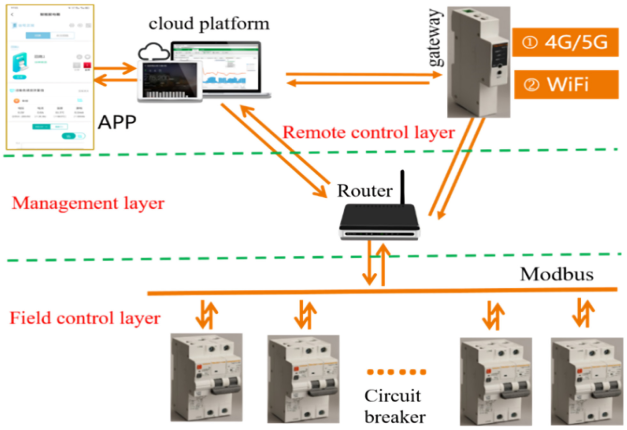

Fig. 14. Architecture of intelligent MCBs [76].

rapid and arc-less interruption of extreme currents. An Arduino microcontroller was used to ensure real-time monitoring and control for swift response to fault occurrences. The Smart Distribution Board enables continuous monitoring of critical parameters like current, power, and energy consumption across various subcircuits, thereby enhancing user awareness and promoting more effective energy management. Now coming to a localized protection system, the research in [76], is centered on the enhancement of miniature circuit breakers (MCBs) to align with the evolving needs of modern power systems. The study delves into three pivotal aspects: 1) high-performance AC and DC general switching technology; 2) digital monitoring; and 3) remote control capabilities of the MCB's operational status. Notably, this article introduces a DC nonpolar breaking technology to bolster the MCB's short-circuit breaking capacity. The MCB underwent and passed a rigorous DC 1000-V/10-kA short-circuit breaking test, showcasing its effectiveness and reliability. Furthermore, the research outlines the development of an intelligent MCB replete with a range of sophisticated functions, including real-time temperature monitoring, remote switching, fault warning mechanisms, and energy metering. This intelligent MCB is developed with digital condition monitoring and remote control software, augmenting its versatility and accessibility. The architecture of the intelligent platform, as depicted in Fig. 14, highlights the framework for remote control and monitoring. This architecture involves mobile phone applications, cloud platforms, gateways, and communication networks. The mobile phone application facilitates digital monitoring of the MCB's operational status and enables remote opening and closing of the circuit breaker, power management, over-temperature alarms, temperature monitoring, automatic trip functions, and more. The entire intelligent circuit breaker system comprises three interconnected modules: 1) the circuit breaker module; 2) gateway; and 3) the power module. The power module's primary function is to provide power, with an input of AC 220 V and an output of DC 12 V, serving the gateway and the single-chip operating mechanism of the circuit breaker module. The gateway, on the other hand, plays a crucial role in network communication and power supply. Communication between the gateway and the circuit breaker modules is facilitated through the Type C data cable, which serves a dual purpose of providing power and enabling communication.

In the context of power distribution, article [77] introduces a sensor-based system designed to monitor fuses in overhead distribution grids. The primary goal of this system is to enhance the efficiency of locating faults that lead to fuse burnout, such as those caused by short circuits or overloads. The system achieves this by utilizing low-cost IoT communication networks, with a focus on scalability and cost-effectiveness. The sensors rely on accelerometers to detect changes in fuse status. Data collected by these sensors is transmitted through the Sigfox network to a supervisory system, providing real-time information on fuse conditions. This approach not only expedites the detection of faults but also improves crucial performance indicators, such as the system average interruption duration index (SAIDI) and average handle time (AHT). SAIDI measures how frequently an average customer encounters extended power outages over a predefined annual time frame [78]. AHT, on the other hand, measures the average amount of time taken to handle a customer inquiry. For the utility, a lower SAIDI and AHT result in a more reliable and cost-effective operation. The sensor-based system's capacity to reduce SAIDI and AHT is not only beneficial for the utility but also enhances the quality and satisfaction of the customers.

These devices, with their multifunctional capabilities and IoT compatibility, hold the potential to revolutionize power infrastructure by enhancing control, safety, and reliability, catering to the growing demand for smart and efficient power management in residential and industrial settings [79], [80], [81], [82], [83].

E. Control of Distributed Energy Resources and Energy Storage Systems

Control and management of energy storage systems (ESSs) and DERs within the framework of the IoT is a pivotal topic in the contemporary energy landscape. IoT plays a crucial role in enabling advanced control strategies for the efficient and dynamic operation of microgrids and distributed energy assets [84]. In this context, various IoT-based control strategies have been developed and deployed to optimize energy management, enhance reliability, and ensure seamless integration of DERs and ESS. These strategies encompass a wide range of applications, from Kalman filter (KF)-based energy estimation [85] to transactive energy management [86], [87], each addressing specific aspects of control, management, and optimization. This section provides an overview of the control strategies employed in the field of DERs and ESS with IoT, shedding light on the diversity of approaches and their potential outcomes.

In [88], the primary objective is to tackle the intricate issues surrounding microgrid state estimation and stabilization within the context of smart grids. The study delves into the potential of smart grid communication systems, sensor networks, and advanced control methodologies. The main objective of this work is the accelerating adoption of DERs as a response to the pressing concerns of global warming and the pursuit of more sustainable energy sources. The research introduces the development of a least square-based KF algorithm for state estimation. To enhance the accuracy and speed of convergence of this algorithm, a least square estimation method is applied to initialize the KF process, ensuring that the initial state estimate is as close as possible to the actual initial state. This approach aims to ensure not only the stability of the microgrid but also the efficient operation of DERs within the network. By optimizing the feedback control parameters using semidefinite programming, the research contributes to improving the overall performance and reliability of the microgrid. Pasetti et al. [89] studied the intricacies surrounding the control and monitoring of DERs within the dynamic context of a smart campus. The research sheds light on the critical importance of effective communication infrastructures in enabling advanced monitoring and control strategies in such environments. A key focal point of the investigation is the daunting challenges posed by the installation costs and complexities associated with traditional wired communication systems, particularly in settings where building distances can vary significantly. To surmount these challenges, the authors promote the adoption of wireless networks, with a specific emphasis on low-power wide area network (LPWAN) solutions, particularly long range wide area network (LoRaWAN). The choice of LoRaWAN is driven by its compelling attributes, including extensive coverage capabilities, low-power consumption, and scalability, making it a desirable option for applications in smart campuses with diverse, geographically dispersed buildings and areas.

With the integration of DERs, the establishment of microgrids is gaining momentum in modern power systems. Batteries and other storage systems have emerged as critical components for storing this energy, addressing the intermittent nature of renewable resources, and ensuring a reliable and resilient power supply. Particularly in remote areas, where traditional grid infrastructure may be limited, these ESS play a pivotal role in balancing supply and demand. To evaluate the performance of different ESS and optimize the transmission of energy, Liu [90] introduced an IoT-based hierarchical ESS to mitigate peak overloads within distributed power generation systems. The study employs gray relational analysis (GRA), to assess and rank the performance of different ESSs based on specified criteria shown in Fig. 15. The assessment encompasses technical specifications [91], [92], [93], economic aspects [92], [94], [95], and social implications, offering a holistic view of the system effectiveness. The lithium battery storage system emerges as the most promising solution, with a correlation value of 0.89, signifying its broad applicability.

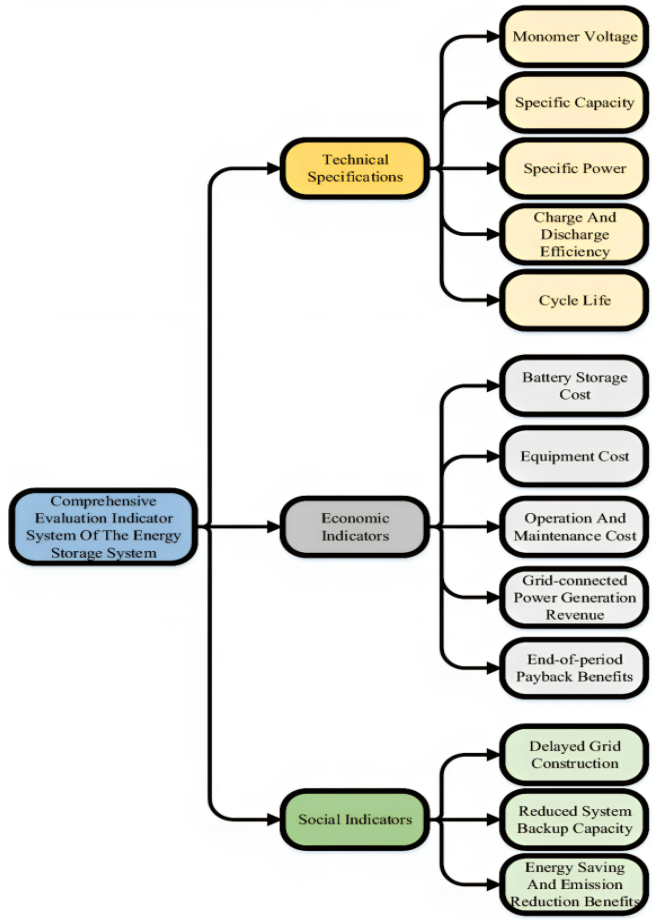

Fig. 15. Specified criteria for ESS [90].

F. IoT-Enabled Energy Consumption

One of the most profound impacts of IoT technology can be witnessed in the domain of energy consumption optimization. It has transformed our homes, cities, and transportation systems, contributing to a smarter, more efficient, and eco-friendly way of living. From smart homes and cities to electric vehicles (EVs) and charging stations (CSs), IoT is playing a pivotal role in ensuring the efficient use of energy resources. Smart homes, cities, efficient power management, EVs, and digitized transportation and parking have attracted increasing interest from the viewpoints of both energy-efficient construction and comfortable living. The availability of a number of Inexpensive Information And Communication Technologies (ICT) and energy technologies enables residents to conveniently integrate digital devices in their houses. In this section, the application of IoT in energy consumption is explored, focusing on various domains.

1) Smart Homes: The concept of a smart home first appeared in the 1930s, envisioning "homes of tomorrow" that offered unprecedented luxury, efficiency, and modern living [96]. However, it took several decades for these promises to materialize fully. Smart homes can be viewed from two complementary perspectives: 1) user-centric and 2) system centric. The former emphasizes convenience, comfort, and modern technology in residential buildings, while the latter focuses on building energy performance, distributed energy generation, and ancillary services facilitated by ICTs [97]. The architecture of a smart home is marked by the interconnectedness of devices, which can range from sensors to appliances and actuators. These individual components, while not inherently smart, become intelligent when they collectively generate, analyze, and act upon data. This data-driven approach allows patterns to be extracted, decisions to be made autonomously, and user interaction to be facilitated. The manner in which devices communicate, share information, and store and process data plays a pivotal role in defining the architecture of a smart home [97], [98], [99], [100], [101].

The concept of a smart home is even more relevant today due to the impact of events like the COVID-19 pandemic, which has accelerated the adoption of digital technologies in homes and highlighted the importance of remote monitoring, automation, and energy efficiency for a safer and more connected living environment [102]. Smart home systems incorporate various communication technologies, including Wi-Fi, Bluetooth, and ZigBee, as well as protocols like TCP/IP. These systems with an array of sensors and switches linked to a central gateway, serve as the primary control interface accessible to users through their digital devices, such as desktops or smartphones [103]. Therefore, considering the applications of IoT in homes, it becomes evident that its versatility has no bounds. The study in [104] presents a design for a smart solar house monitoring and automation system, designed to cater to a wide range of applications. The chosen platform, EmonCMS, harnesses the power of a cloud server to gather data from sensor nodes, adhering to the principles of the IoT. This collected data can be seamlessly displayed, archived, or processed to exert control over various devices within the home. A pivotal component of this system is the NodeMCU, working in conjunction with the ESP8266. It serves as the system's core processing unit, shouldering the responsibility of data collection from the sensors, data processing, and subsequent uploads to the EmonCMS cloud server. Another feature highlighted in the design is the integration of an automatic solar panel cleaning system (ASPCS), a significant innovation that ensures the peak performance and longevity of solar PV panels. The ASPCS is directly controlled through the IoT platform, with the NodeMCU acting as the central hub. It carries out regular cleaning of the solar panels using a brush mechanism and sliding cover, effectively eliminating dust and other contaminants. The system's operation is based on real-time data acquired from various sensors, including light intensity, dust perception, and temperature. There are various other applications of IoT in smart homes as described below:

Occupancy Sensing: Yang et al. [105] introduced an IoT platform designed to address the challenges associated with occupancy sensing and activity recognition in smart homes. They emphasize the growing importance of intelligent occupancy detection for various applications, such as security surveillance and human behavior analysis. The IoT platform is responsible for the real-time collection of channel state information (CSI) [106] measurements, a critical aspect of occupancy sensing that depicts human activity. They used CSI with the OpenWrt operating system to be deployed on various commercial off-the-self routers that enhance the platform's scalability and reduce deployment costs. The authors categorize occupancy sensing tasks into coarse and fine-grained sensing. For coarse sensing like occupancy detection and room-level localization, CSI-based IoT platforms can complete the tasks with manageable computational complexity. Fine-grained sensing, which includes activities like human behavior recognition, requires more extensive signal processing and ML techniques, posing challenges in terms of computational resources and network transmission. To address this, a class estimated basis space singular value decomposition and nonnegative matrix factorization (CSVD-NMF) [107]-based activity recognition algorithm is used. It extracts features from selected CSI data and performs classification in the cloud server. The results showed that occupancy detection achieved an accuracy of 96.8% and human activity recognition achieved an accuracy of around 90%. In [108], a trust-based occupancy detection scheme is proposed for smart residential buildings that address the challenges of using low-cost and nonintrusive sensors with limited training data. The process is initiated by extracting human activity sequences from the raw sensor data, based on the sequence of triggered sensors; subsequently, these extracted sequences undergo a reliable matching scheme for enhanced occupancy detection. Another approach presented in [109] consists of a Raspberry Pi 3 Model B equipped with sensors to measure temperature, humidity, luminosity, and CO_2 levels. A prediction model is used to anticipate the number of occupants based on the monitored environmental parameters. Li et al. [110] proposed a smart home system that senses footstep-induced vibrations to estimate occupancy sensing and tracking location. The system uses seismometers to sense footstep vibrations [111] and uses unsupervised ML techniques to estimate occupancy. Overall, occupancy detection is a valuable technology for smart homes, as it helps to save energy, improve comfort, and enhance security.

Load Monitoring: In the context of smart buildings, a highly impactful application of IoT is the deployment of sophisticated monitoring systems designed to intelligently oversee plug loads, lighting conditions, and the heating, ventilation, and air conditioning (HVAC) systems.

The steadily rising plug load usage, accounting for upto 30% of the total energy consumption in a typical building, leads to issues, such as vampire power consumption [112]. This phenomenon occurs when electronic devices continue to draw energy while on standby or sleep mode leading to an unnecessary 5% to 10% of household power consumption and 1% of global CO_2 emission [113]. In [114], an IoT-based occupancy driven plug load management system, called Plug-Mate, is designed to address the escalating energy consumption of plug loads. This system operates within a custom 4-layered IoT framework, encompassing a Sensing layer, Network layer, Data Processing layer, and Application layer as shown in Fig. 16. Plug-Mate relies on advanced technologies, such as nonintrusive indoor localization, Bluetooth low-energy (BLE) occupancy sensors, and smart plugs, to gather intricate occupancy information and real-time power consumption data. The information is stored in a PostgreSQL cloud database hosted by Heroku, ensuring seamless data retrieval. A Web-based user interface offers personalized control, allowing users to customize automated controls and view historical energy consumption through an interactive dashboard. Plug-Mate has a module component that processes data for plug load identification and automation. This involves capturing high-resolution occupancy information, inferring plug load types, and implementing automated controls based on user

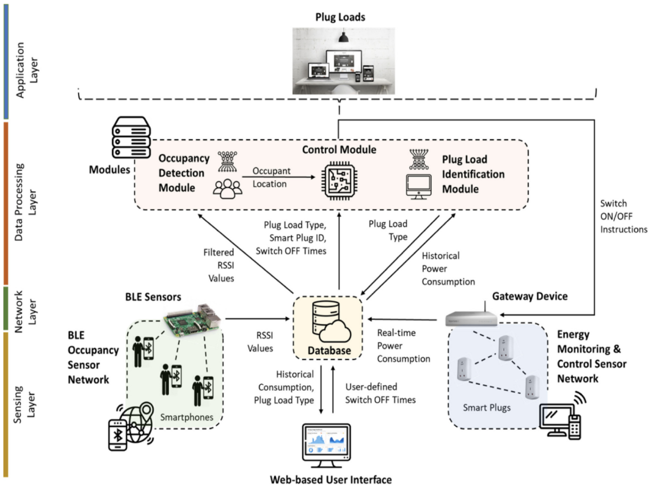

Fig. 16. Architecture and different modules of plug-mate [114].

preferences. The study, conducted over a 5-month period in a university office space, identified “occupancy-driven control with plug load identification and user preference” as the optimal configuration. This configuration achieves a 51.7% energy savings and a user satisfaction score of 4.7 out of 5. The study suggests a potential 7.5% reduction in overall building energy consumption.

Lighting systems in modern buildings leverage advanced technologies like occupancy sensing to optimize energy consumption. In [115], a smart lighting control system, called CS-Light, is introduced that utilizes surveillance camera infrastructure for precise occupancy-driven lighting adjustments. The system’s approach involves using camera feeds to estimate both the illuminance of specific regions and to identify areas with sustained human presence. CS-Light utilizes camera images processed through an object detector, specifically YOLO-V3 [116], to identify and extract coordinates of human objects and employs a binary KNN-based patch classifier for illuminance estimation. This methodology enables the system to achieve a 53% reduction in lighting energy usage, particularly during daylight hours with normal occupancy levels. Numerous other studies depend on diverse sensors or cameras for occupancy monitoring [117], [118], [119], [120], [121]. While these methods prove to be efficient, they result in user discomfort and increased expenses. In response to this challenge, Zou et al. [122] introduced another occupancy-driven lighting control system called WinLight. This system aims to tackle the substantial energy consumption associated with artificial lighting in buildings, constituting a significant 19% of total energy usage [123]. The system utilizes Wi-Fi-based nonintrusive occupancy sensing system (WinOSS) to estimate occupancy information. WinOSS determines the user’s location by utilizing data from their mobile devices without the use of additional sensors. The real-time location of occupants, estimated by WinOSS, is transmitted to a MySQL occupancy database. The WinLight server, acting as the central unit, uses this database to compute appropriate brightness values for each lamp based on occupancy level. These computed values are then transmitted as adjustment commands to the lighting control system. ZigBee facilitates this communication between the centralized lighting control system and the local controllers integrated within each lamp, ensuring precise actuation of brightness adjustments. The system was implemented in a 1500 m^2 office in Singapore, demonstrating substantial energy savings.

In addition to lighting and plug loads, another substantial component of energy consumption in a typical building is associated with HVAC systems. Approximately 60% to 70% of the total energy usage in a building is associated with HVAC systems, and inefficient operations within these systems can contribute to as much as 20% to 30% of the overall energy wastage [124]. To mitigate the considerable energy wastage associated with inefficient HVAC operations, innovative approaches, and technologies have been introduced. The research in [125] highlights the drawbacks of conventional manual thermostats and schedule-based HVAC control, proposing an innovative solution through the fusion of optical (OP) and infra-red (IR) cameras to establish an occupancy-based HVAC control system. The images captured by the OP and IR cameras are transmitted through LoRa communication to a Raspberry Pi, where they undergo further image processing to determine occupancy in the field of view. The HVAC systems are deactivated upon detection of vacancy by the “OP+IR”-based sensing system and activated when occupancy is detected. The study emphasizes that this methodology results in a 5 times reduction in miss rates, a 5 times reduction in false positive rates, and a 3 times extension in battery lifetime, ultimately contributing up to 26% energy savings. Another study [126] focuses on the development and implementation of a device named smart airflow system (SAS), which utilizes occupancy tracking to control the airflow within the building. The hardware design incorporates three interconnected subsystems: 1) a smart doorframe equipped with sensors for accurate occupancy tracking; 2) a sensory hub responsible for monitoring indoor climate parameters; and 3) the SAS that dynamically manages airflow with a motorized air damper. The SAS’s control mechanism adjusts airflow in response to real-time occupancy data, contributing to energy savings and maintaining occupant comfort. Chhaglani et al. [127] introduced FlowSense to monitor airflow in HVAC systems through audio sensing, with a particular emphasis on building ventilation. The system aims to predict the state of air vents (whether they are on or off) and estimate the rate of airflow through active vents. The system architecture, as illustrated in Fig. 17, comprises three crucial modules: 1) sensing and filtering; 2) transformation; and 3) prediction.

1) In the *Sensing and Filtering* module, audio signals from a microphone are captured at a sampling rate of 16kHz, considering the lowest native sampling frequency supported on modern smartphones and Arduino-based sensors. The built-in AudioRecord API [128] on Android and the MP34DT05 pulse density modulation (PDM) sensor on Arduino facilitate this process. To enhance privacy and reduce interference, the captured audio undergoes silence period detection, where segments with noise above a predetermined threshold are

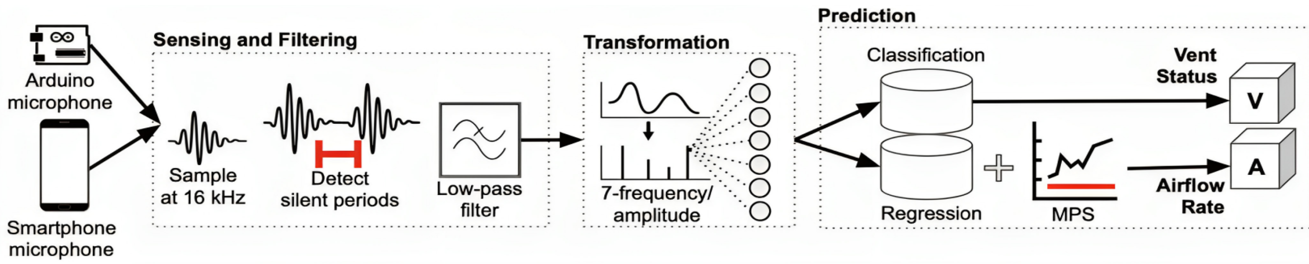

Fig. 17. Component of FlowSense [127].

discarded. The remaining segments, deemed as silence periods, are subjected to a low-pass filter with a cut-off frequency of 375 Hz, removing medium and high-frequency components, including faint human voices.

2) The *Transformation* module follows, employing fast Fourier transform (FFT) on the resulting low-frequency audio signal. This step transforms the signal into the frequency domain, yielding seven audio frequency ranges and their corresponding amplitudes.
3) Finally, in the *Prediction* module, ML models are deployed for real-time predictions. Two simultaneous models operate a binary classification model, using the XGBoost library [129], which predicts the state of the air vent (on or off), while a regression model, also utilizing XGBoost, translates amplitude to predict airflow rate.

The output of the regression model undergoes minimum persistent sensing (MPS) as a post-processing step, identifying a stable minimum airflow rate and enhancing robustness to low-frequency background noise. Implemented on both Arduino and smartphones, FlowSense demonstrates accuracy, surpassing 90% in predicting vent status and achieving a 0.96 mean squared error (MSE) in airflow rate. This approach provides a valuable contribution to the field of indoor air quality monitoring.

Amid challenges, such as COVID-19, the critical role of HVAC in energy demand emphasizes the need for adaptive control methods. The introduction of artificial intelligence and digital twins paves the way for dynamic and intelligent control techniques, with model predictive control (MPC) emerging as a promising solution [130]. The study [131] highlights the evolving landscape with the integration of ML, specifically reinforcement learning (RL) and time-series forecasting (TSF), to transform MPC into a data-driven predictive control method. The integration of RL and TSF is presented as a sophisticated approach, wherein RL agents are trained within a simulated environment constructed using building information modeling (BIM). Simultaneously, TSF utilizes deep neural networks to provide real-time predictions of future environmental changes. The long short-term memory (LSTM), as part of the neural network architecture, contributes by processing time-dependent sensor data, ensuring that past information is appropriately considered for accurate prediction. The study showcases the data-predictive control method achieves a 17.4% reduction in energy consumption and a 16.9% improvement in predicted mean vote (PMV) [132], [133], representing thermal comfort. This integration of RL [134], TSF, and LSTM [135] forms a robust framework for optimizing HVAC operations in smart buildings.

Fall Detection: The integration of smart home technologies with health monitoring has become a transformative force, revolutionizing our approach to well-being within the comfort of our residences [136]. This intersection marks a profound shift in healthcare, harnessing the capabilities of the IoT to introduce innovative solutions for health management. A particular emphasis is placed on the critical aspect of fall detection, acknowledging its paramount importance in addressing health challenges [137]. Falling is identified as one of the simplest yet significant causes of traumas and major injuries, such as traumatic brain damage or fractured bones, particularly affecting the elderly [138]. Statistical data reveals a concerning frequency of falls among individuals aged 65 and above, with 30% experiencing falls annually, escalating to 50% for those aged 81 and beyond. The repercussions of these falls are substantial, as evidenced by the alarming statistic that nearly 45% of nursing home admissions result from falls, with approximately 20% leading to significant traumas [139]. The fear of falling exacerbates the negative effects, diminishing a patient's confidence and contributing to social isolation, restrictive activities, and potential depression [140], [141], [142]. Recognizing these problems, the study in [143] presents an IoT-enabled system designed for fall detection in the elderly population. The research focuses on implementing a sophisticated system incorporating low-power WSN, big-data analytics, smart devices, and cloud computing. The core of the methodology revolves around a wearable sensor node equipped with a 3-D axis accelerometer or gyroscope. To enhance energy efficiency, the researchers utilized a modified nordic radio frequency (nRF) module. This wearable device communicates using the 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Network) protocol, establishing connectivity with IoT gateways for real-time fall detection. One notable aspect of the study is the application of ML models, particularly an LSTM network, for processing and analyzing sensor data on an IoT gateway. The research delves into various factors affecting system performance, including sensor positioning, sample rates, and the impact of different sensors on energy consumption. Fig. 18 depicts the deployment of wearable sensor nodes on individuals, showcasing how the accelerometer captures motion data. The communication pathways between the sensor nodes, IoT gateways, and the cloud are illustrated, highlighting the flow of data in real-time fall detection scenarios. The system attained a fall detection

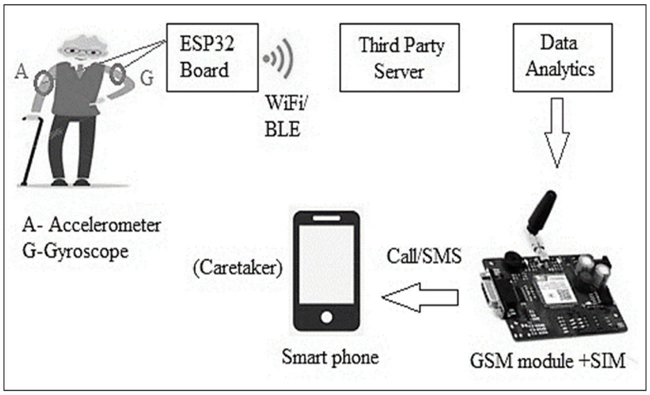

Fig. 18. Representation of key components on FDS [143].

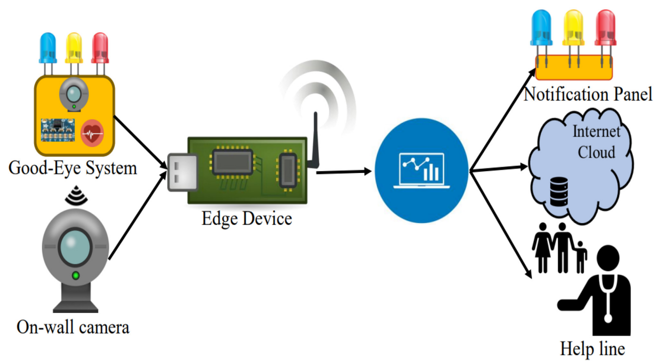

Fig. 19. Good-eye [144].

accuracy rate of 95.87%, making it a valuable contribution to the field of elderly care technology. Another study [144] introduces the Good-Eye System, an IoT-enabled Edge Level Device designed to address the crucial issue of fall detection in the elderly population. The Good-Eye System, depicted in Fig. 19, encompasses a combination of physiological and computer vision systems. It includes a wearable with on-site cameras and a remote wall-mounted camera for continuous monitoring. The LED lights integrated into the system play a vital role in alerting the user to the fall condition, introducing a visual alert element to the system. Bayesian filtering is applied to the camera orientation sensor, enhancing the accuracy of the system in capturing changes in the user's orientation [145]. The proposed system not only aims to detect falls but also predict them, contributing to a more proactive approach to elderly care. The integration of both wearable and off-site devices enhances the overall accuracy of the system. The proposed model is validated using the Person Falling Data set, demonstrating an approximate accuracy of 95% in differentiating between sitting and falling events. The proposed model represents a significant advancement in fall detection devices, with potential applications in healthcare.

However, in a home environment, particularly for older individuals, wearing wearable devices or carrying smartphones may not be feasible, presenting a challenge to practical implementation. To tackle this issue, the study in [146] proposed a fall detection system (FDS) employing a passive and device-free approach, thereby eliminating the necessity for wearable sensors or specialized hardware installations. Instead, it utilizes the widespread WiFi framework in smart homes. The hardware platform, depicted in Fig. 20, involves commercial WiFi devices that capture disturbance signals induced by human motion within the smart home environment. These signals are then transmitted to a data analysis platform for further processing. To enhance the accuracy of the collected data, a discrete wavelet transform (DWT) method is applied to eliminate random noise [147]. The de-noised data is subsequently fed into a recurrent neural network (RNN) model for motion classification and automatic identification of fall status [148], [149], [150]. The proposed FDS demonstrates high accuracy, reaching approximately 90%, across different environments, such as dormitories and laboratories. In addition to its technical aspects, the study emphasizes the practical implementation of the FDS as a consumer mobile application. Users can receive timely fall information and warnings through the mobile application, enabling them to take prompt emergency measures and potentially save lives.

2) Electric Vehicles and Charging Stations: EVs are emerging as promising solutions to environmental problems, but face challenges due to inadequate charging infrastructure [151]. However, the widespread adoption of EVs encounters significant hurdles, primarily attributed to the inadequacies in charging infrastructure [152]. It is crucial, from the perspective of power system operation, to ensure the seamless and efficient functioning of the charging infrastructure. Reliable and well-maintained CSs are essential not only to meet the increasing demand for EV charging but also to contribute to the overall stability and resilience of the power grid. Moreover, the proper scheduling of CSs plays a pivotal role in enhancing accessibility and convenience for EV users.

In [153], the study presents an IoT-based approach to optimize the charging scheduling of EVs in real-time. The proposed solution introduces a server-based forecasting application that serves two main purposes: 1) scheduling management to reduce waiting times and 2) recommending CSs with economic costs and reduced charging times, as depicted in Fig. 21. The CS selection algorithm plays a crucial role in providing relevant information to EV users by actively monitoring CS status, tracking EV location through GPS, and utilizing real-time data to precisely estimate the state of charge (SOC) based on battery drainage rate. In another study conducted Calvillo et al. [154] delve into the intricate dynamics of urban energy systems, with a specific focus on the intricate interplay between DERs and EVs within a residential district. The study introduces a sophisticated linear programming model designed to optimize the operation and planning of DERs, which encompass a spectrum of energy resources, such as PV panels, air-source heat pumps, stationary batteries, and demand response schemes. On one hand, the model takes into account the operation of electric public transport systems, particularly metro systems, while concurrently evaluating the utilization of EVs. This model's key innovation lies in the interconnectedness of EVs and metro systems, where the recuperation of energy from the metro's regenerative braking is stored within the batteries of

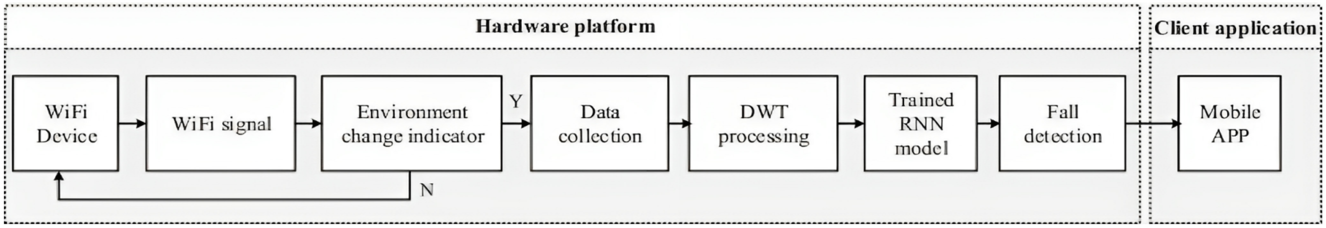

Fig. 20. Sequential processes of the FDS [146].

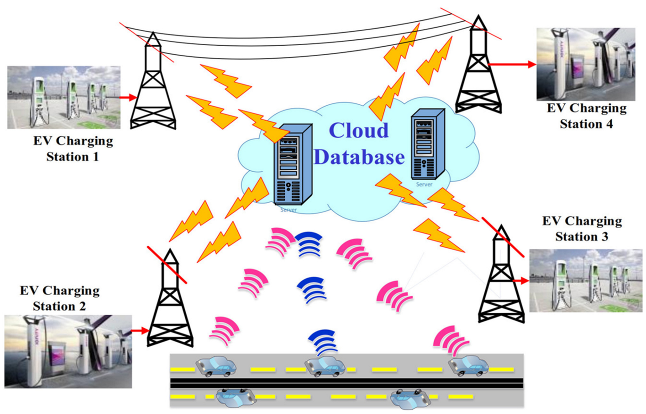

Fig. 21. Real-time visualization of CS availability and EV location tracking [153].

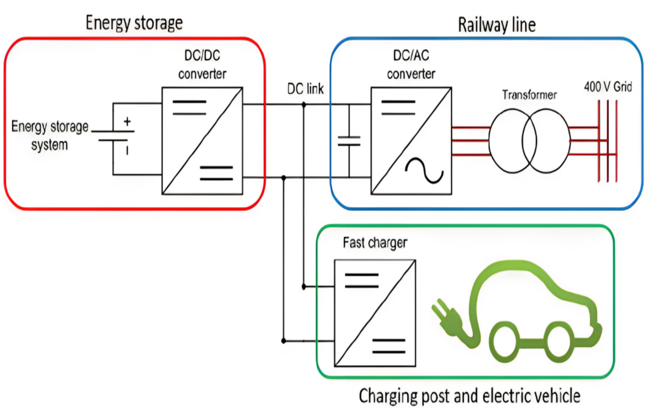

Fig. 22. EV and metro system interconnection [154].

EVs as shown in Fig. 22. The integration of IoT will allow for the coordination of EV charging with the metro system's energy and the distributed energy generation and consumption patterns. Through real-time data collection and analysis, the system can determine the optimal times for EVs to charge, considering factors, such as metro demand, solar irradiation, and electricity prices.

Chen et al. [155] highlighted the advantages of mobile CSs (MCSs) over fixed CSs (FCS) in the domain of EV charging. The study emphasizes that the advantages of MCSs lie in their inherent flexibility and adaptability, attributes amplified by the integration of the IoT. While FCSs have been recognized for their convenience, the authors argue that the dynamic nature of EV users' arrival and the variability in power supply requires a specialized approach in MCSs. The economic model developed in the study plays a pivotal role in enhancing the profitability of MCSs, considering both power consumption a costs for controlling outlets and satisfying EV users' power demand. This article formulates the optimization problem as a stochastic one, accounting for the variable renewable power supply and the random arrival of EV users. In response to this complex optimization challenge, the authors propose a Lyapunov-based online distributed algorithm. The Lyapunov-based approach involves formulating the charging problem into two subproblems. The first subproblem focuses on determining the optimal distribution of power to EV users, considering their dynamic arrival patterns. The second subproblem addresses the control power of MCS's outlets to stabilize the queue backlog efficiently. By using Lyapunov optimization theory [156], [157], [158], the algorithm ensures that the queue backlog remains stable over time, contributing to a more reliable, efficient, and a practical solution for real-world charging services. Another study [159] delves into the optimization intricacies of dynamic wireless charging EV (DWC-EV) systems, with a particular focus on their application in multiroute environments. DWC technology revolutionizes the EV landscape by enabling remote charging while the vehicle is in motion, utilizing power tracks beneath road surfaces. This innovative approach addresses the limitations associated with conventional plug-in EVs. The research introduces a comprehensive model and algorithm designed to optimize DWC-EV systems, specifically tailored for scenarios involving multiple routes. The optimization objectives encompass minimizing the combined costs of both the vehicle batteries and the power track infrastructure. The optimization problem involves determining the optimal battery size for each route and strategically allocating power tracks, all while ensuring that each route completes its services without encountering energy depletion in the batteries. The PSO algorithm is employed as a powerful tool to solve this complex multiroute optimization problem efficiently. In essence, these research studies lay a robust foundation for understanding and optimizing the deployment of IoT-enabled EV charging systems in complex urban public transportation scenarios, paving the way for further investigations into modeling and operational considerations.

3) IoT-Enabled Advanced Metering Infrastructure: The integration of smart meters into the IoT has become a pivotal factor in reshaping the landscape of energy systems. This transformative synergy involves the integration of smart meters, two-way communications networks, and data

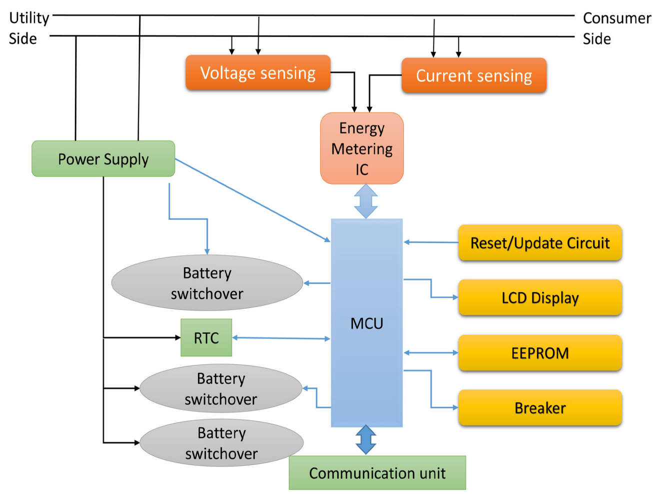

Fig. 23. Internal architecture of smart meter [161].

management systems, collectively known as advanced metering infrastructure (AMI) [160]. The advent of AMI brings forth a myriad of advantages, empowering utility companies to streamline device connections, automate meter readings, and enhance customer billing processes. By harnessing the capabilities of smart metering, IoT connectivity, and data analytics, utility providers can not only optimize service delivery but also foster collaborative efforts with consumers in managing consumption and pricing dynamics. The local monitoring of energy consumption through gas and electricity smart metering, enriched by the integration of IoT sensors, enables the collection of real-time, comprehensive data. This data serves as the lifeblood of smart grids, empowering utility companies to aggregate and manage service delivery, monitor grid health remotely, and achieve sustainability goals.

As depicted in Fig. 23, the internal structure of smart meters reveals a sophisticated integration of high-tech components, including the microcontroller unit (MCU), power supply unit, energy measurement unit, real-time clock (RTC), and communication facilities [161]. The MCU, serving as the heart of the smart meter, orchestrates critical operations, such as communication with the energy metering IC, calculations based on received data, display of electrical parameters, and tamper detection. The power supply unit ensures continuous functionality through AC-DC converters and a supplementary switchover battery. In [162], a unique distributed metering system built on IoT principles is introduced. This system features 3-phase smart meters that provide bidirectional communication, self-regulation, and auto-updating capabilities. Importantly, these meters are capable of employing multiple algorithms for grid management, which can be modified in real-time. The innovation is based on the use of these meters with cost-effective hardware. Testing on the digital real-time simulator, Opal-RT, confirmed the system's efficiency. The evaluation results showed that the data transmission latency complies with IEC 61850 standards, indicating the operational reliability of the infrastructure. Additionally, this advanced system can quickly identify and resolve network problems. The architecture's compatibility with established communication protocols and device management tools was also highlighted, making it a versatile and forward-compatible solution for the evolving energy sectors.

IV. Real-World Case Studies and the Impact of IoT in Power Systems

This section provides a detailed exploration of applications and examples illustrating how IoT has been utilized to enhance the reliability, efficiency, and sustainability of power systems. Through an in-depth analysis of diverse case studies, the tangible impact of IoT on shaping the trajectory of power systems in the real world is revealed. Whether it's smart grids optimizing energy distribution or IoT-enabled devices transforming consumer interactions, these case studies offer valuable insights into how IoT manifests its influence in practical scenarios. Each case study stands as evidence of the dynamics of the power sector.

Building on this exploration, Schneider Electric offers valuable insights into the evolution of maintenance strategies for circuit breakers, illuminating the transition from traditional reactive or preventive approaches to a more advanced predictive model [163]. Emphasizing the necessity for enhanced mean time between failures (MTBFs) and cost optimization, the predictive model incorporates sensor and software technologies for real-time monitoring of circuit breaker health. Analysis of operational and environmental parameters facilitates automated maintenance decisions, reducing failure risks, and enhancing safety. Based on insights from this shift, the findings from the ARC Advisory Group reveal notable outcomes, including a 55% reduction in unexpected failures, a 50% decrease in maintenance costs, a 30% increase in MTBF, and a 30% improvement in machinery availability [164]. The report also underscores the impact of environmental factors, such as humidity, salt, and sulfur dioxide, on circuit breaker aging, highlighting the significance of continuous monitoring. ABB, another prominent player in electrification and automation technology, collaborated with VividCloud to tackle challenges associated with large transformers on the electrical power grid. These intricate devices, equipped with numerous sensors, traditionally stored data internally, requiring manual downloading. ABB aimed to revolutionize these transformers into intelligent, connected, IIoT devices, necessitating significant software upgrades. VividCloud developed the CoreTEC system, incorporating components, such as a runtime executive, license agent, persistence engine, and more. This system empowers operators to configure, control, and monitor transformers, effectively handling data from various sensors. CoreTEC seamlessly communicates with SCADA systems, embedded devices, and remote storage platforms using industrial protocols, thereby enhancing data accessibility. The successful deployment of CoreTEC resulted in substantial cost savings [165]. Enel Green Power, in collaboration with ABB, embarked on the PreSAGHO project, employing predictive and condition-based maintenance solutions through the ABB Ability$^{\text{TM}}$ Collaborative Operations Center in Genoa, Italy [166], [167]. Over a 36-month period, the project targeted

33 hydroelectric plants with approximately 100 power generating units. The initiative aimed to enhance sustainability, reduce maintenance costs, and optimize the performance of Enel's hydroelectric fleet. ABB's expertise in predictive diagnostics and digitalization facilitated the identification of crucial parameters for efficiency, leading to the detection of eight failure predictions. This data-driven approach allowed Enel Green Power to implement proactive maintenance actions, ultimately improving the overall performance of their hydro plants. The ongoing collaboration emphasizes the importance of centralized data analysis, enabling informed decision making and streamlined maintenance processes for sustainable and efficient operations.

The incorporation of GE's digital energy applications in power systems has resulted in transformative economic and environmental benefits through advanced digitization and IoT integration. Noteworthy case studies illustrate the tangible impact of these digital solutions [168]. For instance, a major electric utility strategically implemented GE's digital asset performance management (APM) solution across its extensive wind power fleet, spanning various regions and turbine manufacturers. This initiative resulted in a substantial reduction in wind turbine downtime, translating to over \$3 million in savings and significantly enhancing overall fleet production and revenue [168], [169]. GE's differentiated approach, incorporating a comprehensive value validation methodology, ensured that the investment decision was grounded in both qualitative and quantitative values, garnering consensus among stakeholders. Additionally, GE played a pivotal role in enhancing operational reliability at Engro Corporation's Powergen Qadirpur plant in Pakistan, leveraging digital power generation solutions. The success of this collaboration led to a ten-year agreement to extend GE's APM solution to six power plants in Nigeria and Pakistan, with a combined expected generation capacity of up to 1600 MW. CENAL's Karabiga Steam Power Plant in Turkey achieved substantial annual savings exceeding \$700 000 and a 15% reduction in NO_x emissions through the implementation of GE Digital's Boiler Optimizer [170]. As Turkey transitions its energy production, coal power plants like Karabiga play a crucial role, necessitating stable delivery with minimal emissions. GE's digital solution, leveraging Artificial Intelligence and ML, optimized operations by stabilizing combustion temperature and providing efficient soot blowing capabilities. The Boiler Optimizer analyzed data from over a thousand sensors, dynamically adjusting operating settings for optimum performance and reducing harmful emissions [171]. This digitalization not only led to significant cost savings but also improved the plant's environmental impact, showcasing the efficacy of GE Digital's technology in enhancing the efficiency of power plants. These implementations underscore the vast economic potential of digitalization in energy.

The Digital Wind Farm by GE is a holistic software and hardware solution designed for 2 and 3-MW wind turbines [172]. This comprehensive system integrates GE's turbines with a predictive analytics software platform, Predix, and performance optimization controls technology. Over a wind farm's lifespan, this solution has demonstrated the potential to enhance energy output by up to 20%. Predix acts as the digital infrastructure, enabling the collection, visualization, and analysis of unit and site-level data in real-time [173]. By leveraging predictive modeling based on diverse data inputs, the Digital Wind Farm facilitates advanced planning for turbine operations, efficient maintenance strategies, and timely warnings for potential unplanned events. This not only improves operational efficiency but also generates increased output and revenue for users. GE's digital power plant (DPP) solution, a suite of digital applications optimizing power plant performance, presents a substantial opportunity for global emissions from power plants by up to 10%, equivalent to removing all cars in the United States from the road. This represents a \$200 billion opportunity for the power industry [174]. Moreover, comprehensive digital grid deployment globally could potentially reduce electricity consumption by 12% and decrease carbon dioxide emissions by up to 2 billion metric tons by 2030 [175], [176]. Beyond emission reductions, the digitalization of electricity holds promise in addressing global water scarcity, potentially saving over 300 trillion liters of water by 2030 across various sectors [177]. The Digital Hydro Power Plant, incorporating GE's intelligent condition monitoring system (iCMS), represents a pivotal advancement in hydropower. By utilizing ML techniques, iCMS enhances monitoring and maintenance, potentially boosting output by 1% globally [178]. This innovation translates to substantial economic benefits, with iCMS capable of saving up to \$4000/MW/year and generating nearly \$5 billion in operational cost savings annually when applied across the global hydropower fleet. Beyond economic gains, the increased efficiency contributes to a significant reduction of 17 million metric tonnes of global carbon emissions, akin to removing 41 million cars from the road [179]. The economic benefits of energy digitalization extend beyond the power industry, influencing broader economic and environmental landscapes.

The Port of Kiel has implemented a cloud-based power monitoring solution by Siemens Smart Infrastructure for its shore power system, covering electricity demand for ships at Ostseekai and Schwedenkai [180]. This innovative system, saving over 8,000 tons of CO_2 annually, enables continuous monitoring of energy consumption in the terminal building and at shore power connecting points. Leveraging Siemens' IoT data platform, MindSphere (now known as Insight Hub [181]), the solution allows systematic energy data management, ensuring efficient operations [182]. Operators have real-time access to electrical values, facilitating consumption analysis, fault identification, downtime avoidance, and improved maintenance planning. The Port of Kiel's commitment to systematic power data recording showcases its pioneering role in climate protection, contributing actively to sustainability. Derichebourg multiservices, a facility services provider, has implemented Siemens subsidiary Enlighted's IoT solutions at its new headquarters near Paris, integrating smart sensors directly into LED lights [183]. This innovative approach enables Derichebourg Multiservices to achieve significant energy savings, aligning with both its environmental objectives and French regulations mandating a 40% energy reduction by 2030. The IoT sensors continuously assess data to monitor and control energy consumption, with wireless technology facilitating a swift six-week installation. The collected data not only enhances the building's energy efficiency but also offers valuable insights into environmental conditions and occupancy, presenting opportunities for further optimizations and additional services for occupants. This initiative reflects a broader trend in leveraging digitization and IoT for sustainable and user-centric building management. Silicon Valley Power, the municipal utility for the City of Santa Clara, California, has transitioned to Siemens' EnergyIP meter data management software-as-a-service (MDM SaaS) to upgrade its older version of the EnergyIP MDM solution [184]. Serving a community of innovative and high-tech companies, the utility sought a solution that would enhance capabilities, reduce costs, and ensure cybersecurity. The SaaS option allowed for a virtual system upgrade, minimizing service disruptions and installation costs [185]. The cloud-based solution provides regular software upgrades, new features, and maintenance, improving staff efficiency and potentially saving around \$100 000 per year. This transition aligns with the utility's commitment to energy efficiency and sustainability, earning it a Smart Energy Provider designation from the American Public Power Association.

India Power Corporation Limited (IPCL), a prominent energy company, partnered with Tata Communications to address losses in technical and commercial power distribution [186]. With a focus on reducing outages and gaining operational control, they implemented a smart grid solution with Tata Communications' IZO™ Private Cloud, leveraging IoT technology [187]. The solution incorporated IoT devices to monitor crucial parameters and SIM-based GPRS for real-time data transfer to the cloud. Tata Communications' IZO™ Private Cloud facilitated resilient connectivity, enabling IPCL to cut power outages by 20%. The integration of smart meters with transformers allowed for proactive monitoring, reducing aggregated transmission and commercial losses by 3%. This smart grid solution stands out as a model for infrastructure and connectivity design, showcasing the benefits of digitization in enhancing operational efficiency and reducing environmental impact. Tata Power, the largest integrated power company in India, partnered with Tata Communications to launch an IoT-enabled smart consumer substation (CSS) in Mumbai [188]. This state-of-the-art CSS solution provides an overview of substations across different zones, enabling the monitoring of distribution substations in the field. The system delivers timely alerts on a visual dashboard accessible via handheld mobile devices, allowing field staff to proactively address events [189]. With the implementation of this technology, Tata Power aims to enhance the monitoring of substations and distribution transformers, providing customers with a world-class power supply experience. Tata Consultancy Services Intelligent Power Plant software (TCS IP2) stands as a pioneering digital solution driving sustainable, flexible, and autonomous power generation, addressing crucial priorities for utilities [190]. By harnessing artificial intelligence, IoT, and digital twin technologies, TCS IP2 optimizes the performance of power plants, demonstrating its versatility by extending to renewable sources like wind, solar, and grid-scale batteries. This intelligent platform collects and analyzes historical and real-time data from power plant systems, utilizing over 3,000 sensor inputs and more than 20 000 set-point combinations in real-time decision advisory. Comprising modules like IP2 Insight, IP2 Performance, IP2 Maintenance, and IP2 Studio, along with purpose-built use cases, TCS IP2 significantly enhances power plant reliability, flexibility, and cost efficiency. In thermal power plants, predicted KPI thresholds, real-time insights, and alert systems equip operators with proactive monitoring capabilities. This results in a noteworthy reduction in auxiliary power consumption and a simultaneous increase in power sales by up to 1%, showcasing the platform's impact on economic efficiency. TCS IP2 optimizes combustion processes, lowering plant heat rate by 0.5% to 1%, while also achieving up to an 8% reduction in harmful gas emissions, contributing significantly to environmental sustainability. Moreover, the platform's predictive maintenance capabilities lead to up to a 20% reduction in maintenance and operations costs, driven by accurate failure predictions with an 85% accuracy rate. Additionally, it enhances plant availability by up to 2%, improving asset health in both part and full-load operations. In the realm of renewable power plants, TCS IP2 provides real-time insights, dynamic KPI monitoring, and efficient alert systems, ensuring optimal performance. The platform enables up to a remarkable 40% reduction in maintenance and inspection costs through the implementation of advanced AI, positively impacting the economic aspects of renewable energy generation. Improving plant uptime by 0.5%-1%, TCS IP2 plays a pivotal role in enhancing operational reliability. The utilization of advanced AI algorithms further reduces curtailment by up to 1%, ensuring efficient energy utilization and emphasizing the platform's positive environmental impact. In summary, TCS IP2 serves as a potent facilitator for the economic, environmental, and operational dimensions of both thermal and renewable power plants. The platform presents a significant potential for annual savings, estimated at \$3-4 million per GW of capacity [191]. Furthermore, the Indian Government has initiated the Restructured Accelerated Power Development and Reforms Programme (R-APDRP) with the goal of implementing IT-enabled systems for energy accounting/auditing and introducing supervisory control and data acquisition (SCADA) in major cities [192].

According to the World Economic Forum, the power industry could witness a value stream of \$1.3 trillion through service platforms, smart devices, and advanced analytics [193]. APM solutions alone can generate over \$2 trillion in value by reducing operational expenses and eradicating unplanned downtime. This digital transformation also contributes to a cleaner and more prosperous world, with estimates suggesting a 20% reduction in global carbon dioxide emissions by 2030, accompanied by cost savings of \$4.9 trillion, including reduced electricity and fuel expenditures. Another study conducted by Accenture and the global e-sustainability initiative (GESI) adds a comprehensive perspective to the environmental advantages of digitization. This study suggests that by 2030, a world empowered by IIoT can achieve enhanced cleanliness, and prosperity. The implementation of Internet-enabled solutions through ICT has the potential to contribute to a 20% decrease in global carbon dioxide emissions by 2030.

This would result in a $4.9 trillion reduction in energy costs by the year 2030, comprising $1.2 trillion less in electricity expenditures and $1.1 trillion in decreased fuel expenses [177].

V. IoT Integration Challenges and Solutions in Power Systems

In the context of power systems, the infusion of IoT technologies serves as a transformative force, offering substantial benefits. However, it becomes apparent that alongside these advantages, intricate challenges demand attention. This section explores two key complexities, among many, associated with seamlessly incorporating IoT into power systems, shedding light on challenges and unveiling strategic solutions for resilient integration.

A. Diversified Energy Component Management

The challenge of modernizing the electrical grid to accommodate EVs/plug-in hybrid EVs (EVs/PHEVs), DERs, and smart appliances has prompted significant attention from energy entities, global leaders, and policymakers. With the 2007 Act intensifying the focus on smart grid goals, a variety of technologies, including DERs and EVs/PHEVs, have been integrated into the existing power grid [194]. However, the absence of coordinated controls can lead to adverse effects on the reliability of power distribution components. Addressing this issue, the solution proposed in [195] involves the implementation of a house energy management system (HEMS) designed to coordinate and optimize residential resources without inconveniencing customers while minimizing stress on the distribution infrastructure. It facilitates real-time control and management of all DERs in the house, including storage devices and smart appliances. A pivotal component, the house distributed state estimation (HDSE), collects real-time data from various metering devices within the house, including GPS-synchronized or nonsynchronized measurements. The data transmitted to HDSE undergoes state estimation, resulting in a reliable and validated real-time model of the entire house, serving as the basis for optimization processes and control of DERs and appliances. The optimization model, expressed as a mixed integer quadratically constrained programming (MIQCP) problem, addresses multiple objectives. One primary objective is the minimization of the customer energy costs over a planning period, considering factors such as electricity rates. Another key objective is the control of peak loads, particularly crucial in areas served by vertically integrated utilities. The solution method involves linearizing the quadratic optimization problem using λ-formulation, a piecewise linear technique [196]. The authors used Gurobi Optimization Software 5.6.3 to solve the resulting optimization problem [197]. The output of the optimization software manifests as scheduling control signals for house DERs and smart appliances, offering a promising approach to grid modernization and sustainable management.

In summary, delving into the challenges associated with managing diversified energy components provides valuable insights into the complexities of modernizing the electrical grid. The findings from these studies make a substantial contribution to the overarching goals of grid modernization and sustainable energy management.

B. Cyber Attacks

IIoT applications often face security challenges stemming from wireless communication technology, such as the potential for backtracking attacks, which can compromise source location privacy (SLP) [198], [199], [200]. Additionally, these applications must satisfy energy consumption concerns. To address these issues, Xiong et al. [201] introduced a solution called phantom nodes, rings, and fake paths (PRFs). PRFs offer a unique approach by integrating DERs into the solution. The PRF scheme is primarily designed to protect SLPs by employing both fake and real data packets. Real packets originate at the source node and travel to the sink node through distinct phases. These phases involve transmission to phantom nodes, routing to the ring, and eventually reaching the sink node. Meanwhile, fake packets generated by fake phantom nodes are disseminated throughout the network to confuse potential attackers. The flexibility of PRFs is highlighted by their ability to adapt to complex deployment environments and terrain, as the selection of the ring and ring center is independent of the source and sink node locations.

1) *Ring:* According to [201], a ring is a circular network topology formed by a set of sensor nodes in a WSN.
2) *Ring Center:* It is a specified node within the ring topology, acting as a central point of reference.

PRFs are well-suited for DERs for enhancing data security, efficient and flexible energy management, extended network lifetime, and environmental sustainability. Another challenge in microgrids is the tracking of load changes in real-time, accounting for sudden unit exits and entries, and incorporating various RES like PVs, wind turbines, fuel cells, and micro-turbines. To handle this complexity, Dabbaghjamanesh et al. [202] introduced a fast consensus-based optimization algorithm, which is further enhanced through fuzzy adaptive leadership techniques. This leverages the benefits of fog computing to efficiently manage microgrid operations. The proposed technique is tested through simulations on microgrids with 6 and 14 buses, demonstrating its capability to monitor load changes in real-time and achieve rapid convergence. The contributions of this research include the prevention of direct agent communication, the utilization of distributed optimization techniques, and the provision of optimal dispatch solutions in the presence of both dispatchable and nondispatchable power resources, even when dealing with abrupt changes in load. Furthermore, this article introduces a three-layer cloud-fog-device framework to facilitate data transfer and system topology determination. This enables real-time monitoring and enhances privacy protection.

In [203], the primary focus revolves around mitigating the susceptibility of traditional communication infrastructures to cyber threats within the realm of IoT-enabled EVs. This article introduces a sophisticated algorithm tailored for monitoring and controlling EVs by harnessing the capabilities of the IoT communication network, specifically addressing the challenges posed by false data injection attacks. The conceptual framework adopts a state-space representation for a driverless EV equipped with an onboard vision system, leveraging IoT-embedded smart sensors for real-time data collection, monitoring, and remote control center interaction. A pivotal contribution lies in the proposed optimal state estimation algorithm, grounded in the mean square error principle [204], [205]. This algorithm not only facilitates a comprehensive understanding of vehicle states but also proves resilient in the face of cyber attacks on the communication channel. Furthermore, a semidefinite programming-based optimal control algorithm is intricately designed to adeptly regulate and stabilize the dynamic system states. Through meticulous simulations, the results unequivocally showcase the superior performance of the proposed algorithms, demonstrating their efficacy in accurately estimating and controlling vehicle states within remarkably brief timeframes. In essence, the study plays a crucial role, offering invaluable insights into the meticulous design and fortification of autonomous vehicle systems in an era where cybersecurity is paramount.

In response to the escalating threat posed by large-scale load-altering attacks (LAAs) on high-wattage electrical appliances within the IoT, the study in [206] introduces a groundbreaking cyber-resilient economic dispatch (CRED) concept. The severity of LAAs lies in their potential to disrupt power system stability and security. Notably, this research distinguishes between static and dynamic LAAs (DLAAs), each presenting unique challenges. Static LAAs involve sudden, one-time manipulations of demand, resulting in economic costs and possible load shedding [207], [208], [209]. DLAAs, on the other hand, entail continuous manipulation synchronized with system frequency fluctuations, posing a substantial risk to the frequency control loop [210]. The study makes a significant contribution to the underexplored realm of mitigating the destabilizing effects of LAAs by proposing an online DLAA mitigation technique. The proposed CRED model dynamically utilizes the fast and flexible control of inverter-based resources (IBRs) to counteract the destabilizing effects of DLAA. Crucially, CRED operates in real-time, adjusting the frequency droop control gains of IBRs across the system dynamically. This approach ensures the maintenance of system stability while minimizing overall operational costs. The study introduces the concept of distributionally robust optimization to account for uncertainties associated with system dynamics driven by LAA detection and parameter estimation errors.

Another critical aspect of power system is addressing relay settings change attacks [211]. These attacks involve altering the settings of protective relays, which are essential for detecting and responding to abnormal conditions in the power grid, such as short circuits or overcurrents. An attacker can manipulate these settings to disrupt the normal operation of the power grid, potentially leading to widespread outages and other disruptions. Detecting these subtle changes can be challenging, and preventing such attacks requires robust cybersecurity measures and high-level access control to power grid's systems. Similarly, tripping command injection attacks involve injecting false or malicious commands into the control systems of a power grid to disrupt its normal operation [211]. The goal is to cause equipment to trip or shut down, leading to potential power outages and other disruptions. These attacks are difficult to detect due to the small amounts of false data injected into the control systems and require strong cybersecurity safeguards to prevent unauthorized access and malicious command injections.

In addition to above attacks, several other methods of attacking IoT devices pose significant risks to power systems [212]. These include the following.

1) *Initial Reconnaissance:* Attackers gather information about devices, network, and potential vulnerabilities to plan subsequent attacks.
2) *Physical Attacks:* Physical tampering with IoT devices can lead to unauthorized access and control over the network or device.
3) *Man-in-the-Middle:* Attackers intercept and manipulate communication between IoT devices, potentially altering or stealing sensitive data.
4) *Botnets:* Compromised IoT devices can be used in coordinated botnet attacks, leading to large-scale disruptions, such as distributed denial of service attacks.
5) *Denial of Service Attacks:* Overloading IoT devices or networks with excessive traffic to disrupt normal operations and cause service outages.

To effectively mitigate the numerous cybersecurity threats faced by IoT-integrated power systems, leveraging advanced technologies and innovative approaches has become paramount. Advanced technologies, such as AI/ML, blockchain, and 5G/6G networks, provide promising solutions to these challenges [213], [214], [215], [216].

AI and ML technologies are pivotal in modern cybersecurity frameworks for IoT-integrated power systems. They facilitate anomaly detection, predictive analysis, and automated incident response, enabling the identification and mitigation of cyber threats in real time. AI/ML algorithms analyze vast amounts of data generated by IoT devices, identifying unusual patterns that may indicate potential security breaches. For example, predictive maintenance uses AI to forecast equipment failures before they occur, reducing downtime and enhancing operational efficiency. Similarly, AI-driven load forecasting helps in managing power demand more effectively, optimizing resource allocation, and preventing grid overloads [214].

Blockchain technology has emerged as a promising solution to address cybersecurity challenges in power systems, particularly concerning the IoT and cyber attacks. Liang et al. [215] explored the application of blockchain for countering cyber threats in modern power systems, presenting a distributed blockchain-based protection framework. This framework employs meters as nodes within a network, creating a decentralized and secure infrastructure to enhance the self-defensive capabilities of power systems against cyber-attacks. Unlike traditional centralized approaches, the proposed system leverages the principles of blockchain to establish a consensus-based model that ensures the integrity and security of the power grid. The framework's key features include the use of meters equipped with specific software to generate public and private keys, facilitating secure communication and data verification. Each meter acts as a node in a distributed meter-node network, forming a private blockchain network. The

TABLE I
SUMMARY OF PROBLEMS AND POTENTIAL SOLUTIONS OF IoT APPLICATIONS ACROSS VARIOUS DOMAINS

Topics Covered	Problem Statements	Potential Solutions
• Integration of Renewable Energy Resources • Power Plant Automation Related Ref.: [34], [37], [39]–[41], [43], [46]–[50], [53], [54]	• Unpredictability of solar radiation • Challenges in efficient energy utilization from renewable sources • Inaccurate forecasting of wind power due to its unpredictable nature and difficulty in efficiently managing unpredictable wind energy sources • Real-time monitoring and maintenance in remote areas • Labor-intensive manual oversight in thermal power plants • Operational disruptions due to breakdowns or malfunctions in HT motors • Decreased efficiency of hydro turbines due to silt erosion and cavitation • Unidirectional information flow • Lack of precise forecasting for hydro turbine conditions • Inadequate dam safety monitoring	• Development of a hedging system integrating IoT capabilities for accurate solar radiation forecasting • Introduction of ISEMS using predictive modeling for optimal energy distribution • Enhanced predictive modeling using ML algorithms like SVM, PPM, and LPM optimized with optimization techniques like GA, PSO, etc. • Utilization of logistic regression and NAR neural networks for wind speed forecasting • Use of FPGA-CPU hybrid controllers for real-time processing and multitasking • IoT-based remote monitoring system utilizing sensors for real-time data transmission, cloud storage, and proactive alerts • Implementation of IoT-enhanced smart grid systems for bidirectional data flow, demand-side management, and cybersecurity measures • Integration of IoT with SCADA systems for comprehensive monitoring and control • Utilization of machine learning algorithms for predictive analytics, enhancing accuracy and reliability of forecasting models
• Enhanced System Efficiency and Real-Time Monitoring • Power System Protection • Control of DERs and ESSs Related Ref.: [61], [63]–[65], [68], [71], [73]–[77], [84]–[90]	• Enhancing grid resilience and stable electricity supply • Reduction of transmission losses in electrical grids • Real-time monitoring and predictive maintenance of assets • Integration of IoT in power system protection • Fuse monitoring in overhead distribution grids for fault detection • Optimization of microgrid operation with DERs and ESS • Efficient energy estimation in IoT systems • Optimization of energy management • Cost and complexity of wired communication systems • Performance evaluation and optimization of ESS	• Tracking of substation metrics using FPGA • Integrate D-PMU for enhanced fault analysis and data gathering • Combine DSTATCOM with IoT for improved power factor and quality monitoring • Establish two-way communication between utilities and consumers power supply management • IoT-based DGA-based health assessment system • Power system protection devices like ELSA for rapid fault disconnection and improved safety • Development of SCBs for real-time grid quality monitoring and swift fault management • Utilization of accelerometers for rapid fault detection and enhanced grid reliability • Kalman filter-based energy estimation • Transactive energy management strategies • Least square-based Kalman filter algorithm with semidefinite programming for stability and efficiency • Adoption of LPWAN or LoRaWAN, for wireless communication • Hierarchical IoT-based ESS with GRA ranking for peak overload mitigation
• Energy Consumption • Cyber Attacks Related Ref.: [97]–[101], [105]–[107], [112]–[116], [122], [125]–[138], [143]–[155], [159]–[162], [198]–[205]	• Lack of energy efficiency, inconvenience in residential buildings • Challenges in occupancy detection and activity recognition • High plug load usage leading to energy wastage • Inefficient lighting systems contributing to energy consumption • Inefficient HVAC operations leading to significant energy wastage • Lack of effective airflow monitoring • Inadequate fall detection systems, especially for the elderly • Insufficient EV charging infrastructure • Traditional metering lacks real-time data capture • Backtracking attacks compromising SLP • False data injection attacks • Tracking load changes in real-time	• Use of interconnected devices for data-driven decision making and user interaction • Utilization of IoT for real-time collection of CSI measurements • Implementation of CSVD-NMF based activity recognition algorithm • Development of IoT-based occupancy-driven plug load management system (Plug-Mate) • Integration of advanced technologies like BLE occupancy sensors and smart plugs • Implementation of smart lighting control systems (CS-Light, WinLight) • Wi-Fi based non-intrusive occupancy sensing • Occupancy-driven lighting adjustments • Occupancy-based HVAC control systems utilizing OP and IR cameras • Implementation of SAS for airflow control based on real-time occupancy • Implementation of FlowSense utilizing audio sensing and ML models • Wearable sensor nodes with accelerometers for real-time fall detection • Device-free fall detection using WiFi disturbances • EV charging scheduling and station selection algorithms • Integration of EV and metro systems for energy optimization • Mobile charging stations • Distributed metering systems with bidirectional communication • Introduction of PRFs for protecting SLPs • Optimization algorithm enhanced through fuzzy adaptive leadership techniques

system employs a consensus mechanism, ensuring that data manipulation attempts by cyber attackers are only successful if a majority of channels or meters are compromised. This consensus-based approach sets the proposed framework apart from conventional power system data defense countermeasures.

While AI/ML and blockchain can significantly enhance cybersecurity, a major challenge is the efficient handling of large volumes of data. In this context, *5G/6G networks* can act as enablers by providing advanced capabilities, such as ultralow latency, high throughput, and extensive coverage, to connect numerous devices over large geographic areas [216]. These features are particularly beneficial for power system applications, where real-time data transfer and processing are critical for monitoring, control, and decision-making processes, even in remote or densely populated locations.

By addressing the specific challenges posed by cyber threats in the IoT context, the studies offer robust solutions, marking a significant advancement in the field of cybersecurity for critical infrastructure. The studies provide holistic and innovative approaches to addressing the multifaceted challenges within the IoT-enabled power systems. The integration of detection, localization, and real-time mitigation strategies represents a significant advancement in enhancing the cyber-resilience of power grids against emerging threats.

Table I presents a summary of problems and potential solutions of IoT application across various domains of power system.

VI. Conclusion

In conclusion, this review underscores the pivotal role of IoT in reshaping electric power systems, emphasizing its transformative impact on various facets. The digitalization facilitated by IoT yields numerous benefits, including the enhanced management of energy resources, fostering energy conservation, cost savings, and improvements in reliability, resiliency, security, sustainability, and efficiency within electric power networks. IoT emerges as a transformative force with far-reaching impacts on the economy, society, and the environment. Positive outcomes include increased revenue in power systems, reduced carbon emissions, improved lifestyle convenience, public safety, energy conservation, expense reduction, and the promotion of a healthier living environment. However, alongside the advantages, this article acknowledges challenges related to sensing, connectivity, power management, and security in IoT for power systems. Addressing these challenges is crucial for the sustained growth of IoT, and this article has discussed recommended solutions as steps toward mitigating these issues. Looking toward the future, the integration of advanced technologies, such as AI and ML, blockchain, and 5G/6G, holds the promise of further enhancing and expanding the use of IoT-enabled devices in power systems. These innovations present opportunities to overcome current challenges, paving the way for a more extensive and efficient integration of IoT in shaping the future landscape of electric power systems.

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